THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND FORTY-SECOND GENERAL MEETING of the Institution of Petroleum Technologists was held at the House of the Royal Society of Arts, John Street, Adelphi, London, on Tuesday, April 12, 1932, Mr. JAMES KEWLEY, M.A., F.I.C., F.C.S., M.I.Chem.E. (President), occupying the Chair.

The Secretary read the names of the candidates nominated for election and the following list of members elected :—

As Members.—George William D'Arcy-Evans. William Frank Jelffs. Charles Joseph Johnson. Eric Holdsworth Walker.

As Associate Members.—Frank Victor Moore Bell. David Ralph McKinney.

As Transference to Associate Member.—Thomas Speight.

As Associate.—Richard Henry McDowell.

The President (Mr. J. Kewley), in opening the meeting, said that the subject of spontaneous ignition temperatures of fuels had received much attention as it was the expression of a desire to devise a laboratory test which could evaluate fuels in terms of engine behaviour, particularly in relation to the absence of knock and rough running. An attempt to do this in the case of gas engines was a failure, although some general relation between anti-knock value and spontaneous ignition temperature was established. Eventually the problem had to be referred to the engine itself. In the case of Diesel fuels similar problems had presented themselves, and the papers to be presented that evening would indicate the progress made.

SYMPOSIUM ON SPONTANEOUS IGNITION TEMPERATURES.

Spontaneous Ignition Temperatures of Fuels.

Report by F. A. FOORD, A.F.R.Ae.S. (Air Ministry),

On experiments carried out at the Royal Aircraft Establishment by Squadron-Leader W. Helmore, M.Sc., A.F.R.Ae.S., and F. C. Code Holland, M.Sc., A.I.Mech.E.

INTRODUCTORY.

RESEARCH was started at the Royal Aircraft Establishment in 1928 to examine the ignition characteristics of liquid fuels, injected into air, with a view to considering chemical means of accelerating their combustion. It was recognised that one of the chief defects

associated with the functioning of compression ignition engines was the delay existing between the first injection of the fuel and its subsequent ignition in the combustion chamber.

It was anticipated that the development of the high speed compression ignition engine would demand more rapid ignition of the injected fuel, and it was desired to compare the behaviour of various oils in this respect with a view to determining their relative suitability for high speed compression ignition engine use, and to examine chemical means for their improvement. Before this investigation could be made it was necessary to develop laboratory apparatus for determining the relative spontaneous ignition temperatures of fuels when injected into air.

Factors Influencing Spontaneous Ignition.

It has hitherto been the practice to assign to any individual fuel one definite spontaneous ignition temperature which is usually regarded as the lowest temperature at which the fuel, after an indefinite delay, will ignite.

It is felt, however, that this method is not satisfactory because it shows only one point on what is a definite curve relating delay time with temperature for each particular fuel, and this lowest spontaneous ignition point may not necessarily bear any important relation to the performance of the fuel in a compression ignition engine.

A further difficulty is the influence of any heated surface with which the oil may come in contact, and which, where the lowest temperature at which ignition occurs is regarded as the spontaneous ignition temperature, may so affect the process of combustion as to render the observations valueless.

Such temperatures, although interesting from the point of view of the estimation of the fire risk involved in the use of fuels, do not provide all the information regarding any particular fuel which should be available.

R.A.E. Spontaneous Ignition Temperature Apparatus.

In this apparatus, an attempt has been made to provide information as to the ignition delay of any fuel at various temperatures, from the temperature at which almost instantaneous ignition occurs, down to the lowest temperature at which the fuel will ignite after long delay.

From the attached results it will be seen that for each fuel a curve may be plotted showing temperature against delay period.

In designing the explosion apparatus, the object throughout has been to reproduce as nearly as possible the injection system commonly employed in a compression ignition engine, and also to

endeavour to avoid any contact between the fuel in the liquid phase with metallic surfaces at a higher temperature than the air in the apparatus.

It is not suggested that the delay times and ignition temperatures given are exactly those which would exist in a compression ignition engine. It would in any case be impossible to do this because between individual engines, variations of pressure, turbulence, spray direction, surface temperature of the combustion chamber, etc., must inevitably exist, and all users of such engines are aware of the wide discrepancies present in respect of delay period observed between almost identical types of engine.

By this apparatus, it is only desired to provide a direct basis of comparison, under similar conditions, between various fuels, so that the order of merit shown by the apparatus shall be as nearly as possible the order of merit of the fuels in any given engine. This order of merit, however, will only reflect the properties of the fuels, having regard to ease of starting and ignition delay on injection.

With regard to ease of starting, except where some electrically heated hot-spot is used, it is clear that the method of estimating the tendency of a fuel to ignite in the heated air only should provide the most direct comparison, as the walls of the combustion chamber of a compression ignition engine are necessarily relatively cold in these circumstances and ignition must therefore take place in air only.

Under running conditions, surface effect will in certain engines, be present, but it may be argued that any fuel which will ignite on emergence from the jet without any ignition delay, must ignite in air before it has had time to travel across the combustion chamber to any heated surface.

This ideal has probably seldom been achieved, but it is an ideal which, if achieved would eliminate the considerable disadvantage associated with rough running and inefficient combustion in compression ignition engines.

General Description of Apparatus.—The apparatus consists of (*a*) an electrically heated explosion vessel; (*b*) a fuel injection system; (*c*) an injection timing mechanism; (*d*) an explosion timing mechanism; (*e*) an electrical recording mechanism for indicating the ignition delay; and (*f*) a thermo-couple for indicating the temperature of the air.

The following brief description of the individual parts indicating the general principles involved are given:—

(*a*) *Explosion Vessel.*—This consists of a wrought-iron cylinder about 6 in. diameter and 18 in. long, the sides of which are electrically heated by a resistance wire and suitably lagged and covered.

The top end of the cylinder is formed of layers of steel and asbestos and has orifices for the fuel injection valve, thermo-couple, vent and air tube and a connection for the explosion time recorder.

The fuel injection valve and explosion vessel are so arranged as to give a spray having a cone angle less than the cone angle subtended by the perimeter of the bottom end of the vessel with the point of entry of the fuel into the vessel. This is necessary in order to ensure that the spray does not strike the heated sides of the vessel.

The bottom end of the cylinder is of inverted conical shape, unlagged and separated from the body part by a joint ring of asbestos. This is necessary in order to ensure that any fuel from the jet which may impinge on the bottom does so on a relatively cool surface.

The bottom end has a drain connection to a vacuum pump or equivalent means for scavenging the vessel after each explosion.

The air inlet is arranged tangentially to obtain a scavenging or circulating action and contact with the thermometric device. Fig. 1 shows the general arrangement.

(*b*) *Fuel Injection System.*—This consists of a standard Bosch nozzle testing apparatus, the pump being of the plunger type in which a small quantity of the fuel is trapped in the cylinder and forced past a spring loaded non-return valve.

The pump is operated by a falling weight and lever fulcrumed on the pump base, which ensures that the rate of injection of the charge is constant for each test.

A constant fuel charge is essential, as under engine conditions both the rate of rise of pressure and delay period are affected by this factor, but the effect of minor variations is reduced by injecting a mixture richer than the theoretical mixture for complete combustion.

The general arrangement of the pump is shown in Fig. 2.

The injection valve is of the type in which the fuel pump pressure lifts a spring loaded valve from its seating in the explosion vessel, any leakage of fuel in the body of the valve being led away.

In axial alignment with the valve stem is a central tappet pin, which is guided by the valve casing and, projecting above the latter, is in contact with a rocker block which is pivotally mounted on a fitting secured to the valve casing.

The general arrangement of fuel nozzle is shown in Fig. 3.

(*c*) *Injection Timing Breaker.*—The means for indicating the moment of injection of the fuel consists of a low tension electric circuit which is automatically broken by the opening of the fuel injection valve.

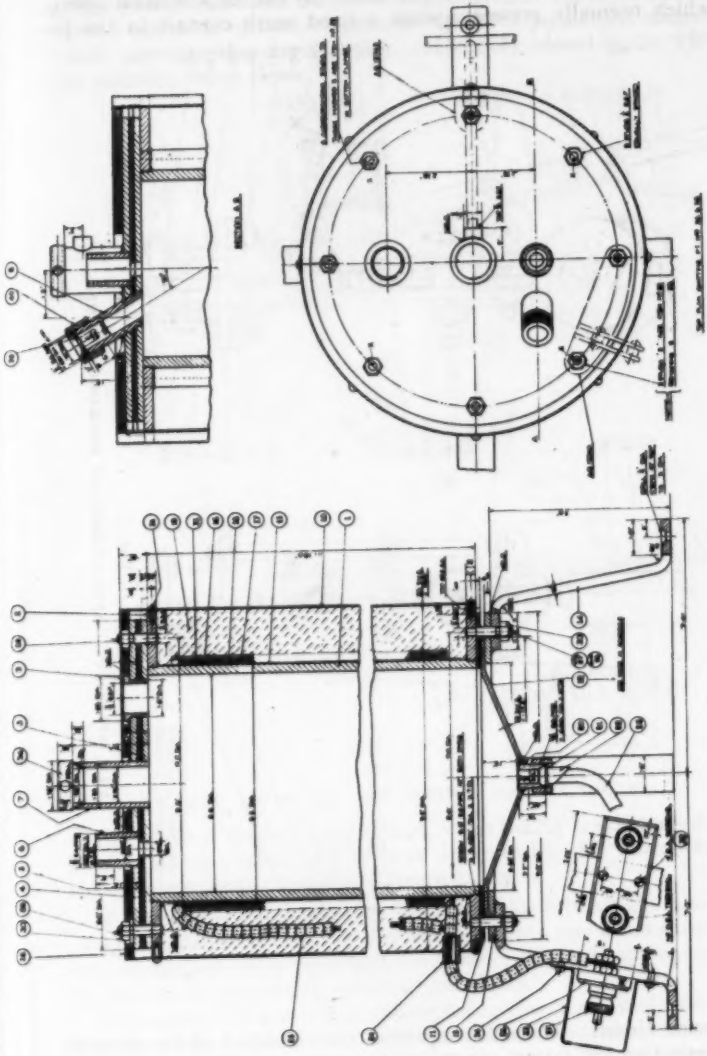


FIG. 1.

S.I.T. APPARATUS. ARRANGEMENT OF CHAMBER.

The rocker block mentioned under (*b*) carries a contact spring, which normally presses against a fixed earth contact in the low

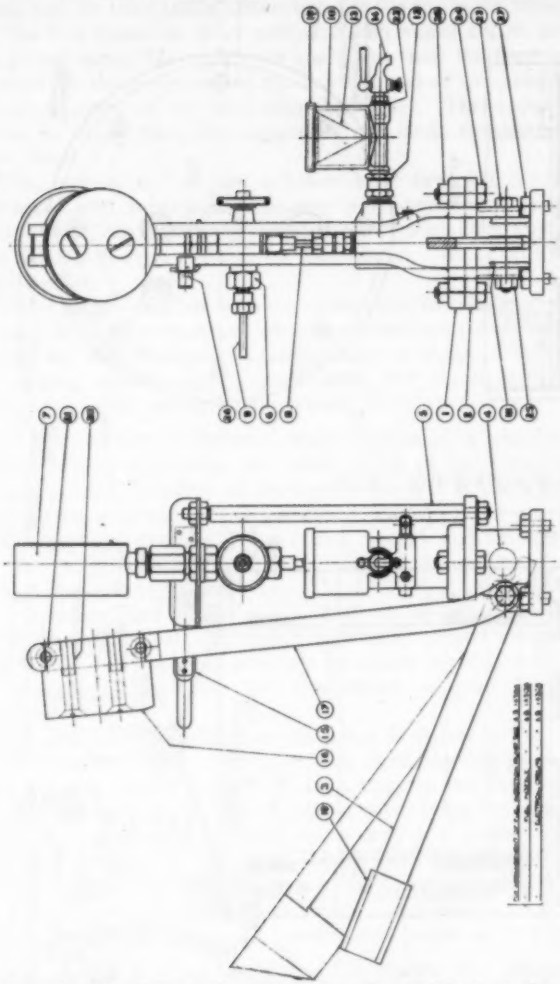


FIG. 2.

S.I.T. APPARATUS. ARRANGEMENT OF MECHANICAL PUMP.

tension circuit. When the injection valve is lifted at the moment of injection the tappet pin moves the contact spring and suddenly breaks the circuit.

The rocker block also carries a laminated arm which, as the low tension circuit is opened, is brought against a permanent magnet, which prevents the circuit being accidentally closed again when the injection valve closes.

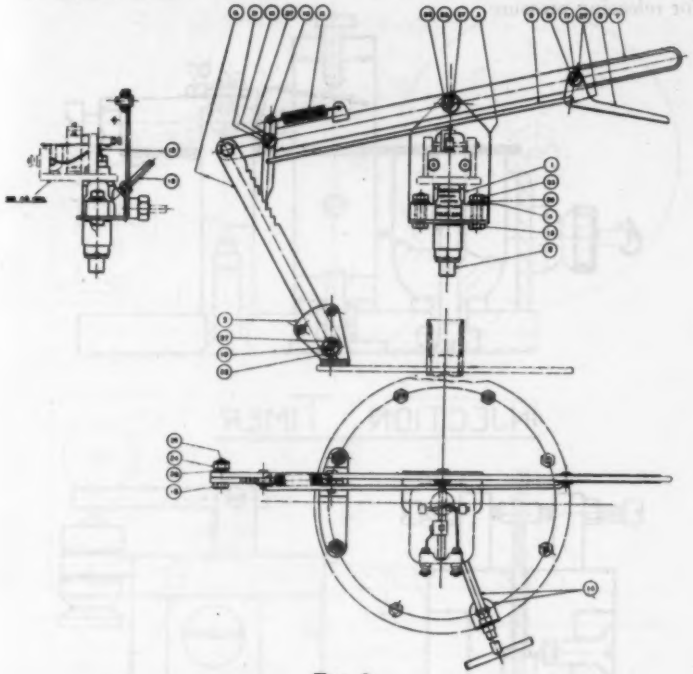


FIG. 3.

S.I.T. APPARATUS. ARRANGEMENT OF FUEL NOZZLE.

The whole of the fuel valve and injection timing breaker assembly is mounted on a retractable lever as shown in Fig. 3. The detail of the injection timing breaker is shown in Fig. 4.

(*d*) *Explosion Timing Breaker.*—The time lag between the moment of injection and the subsequent explosion of the fuel is indicated by the breaking of a low tension electric circuit automatically operated by the rise of pressure in the explosion vessel.

The circuit breaker which accomplishes this is screwed into the top end of the explosion vessel and comprises a disc valve connected to a tappet pin, which is guided in a central sleeve and projects above the latter against a pivoted contact lever on the fitting.

The contact lever is controlled by a hair-spring and carries an earthed contact, which normally rests on an insulated contact.

The disc valve sits on an annular seating and works in a chamber of larger diameter, which is open to the atmosphere through a hole for releasing pressure.

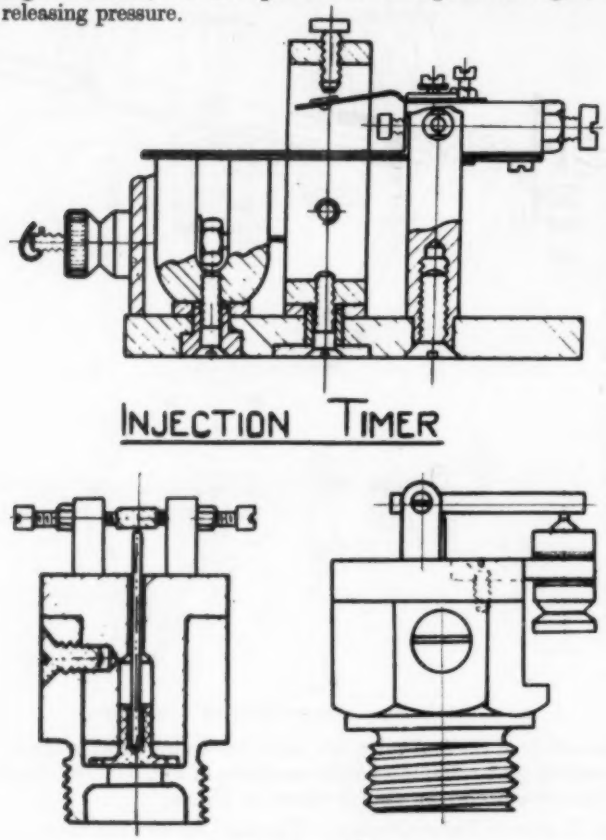


FIG. 4.

SPONTANEOUS IGNITION APPARATUS.

When the disc valve is lifted at the moment of explosion of the fuel, the contact lever suddenly breaks the circuit.

The general arrangement is shown in Fig. 4.

(e) *Electrical Recording Mechanism.*—This recording mechanism (Fig. 5) is a device for obtaining a record of the time lag between injection and explosion which represents the ignition delay period.

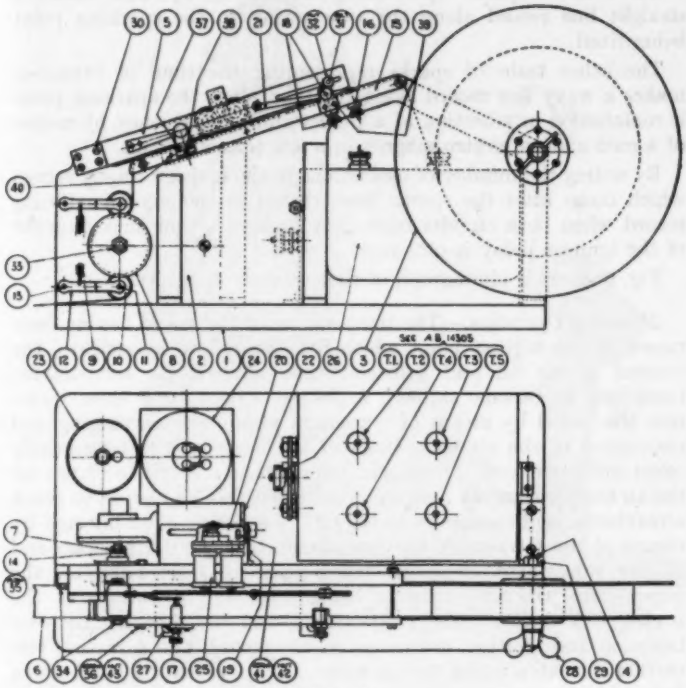


FIG. 5.

S.I.T. APPARATUS. RECORDING MECHANISM.

The two low tension circuits for injection and ignition timing are interrupted at high frequency by tremblers in series with the respective circuit breakers already mentioned.

A separate record of the breaking of each low tension electric circuit is obtained by sparks from sparking points in a high tension circuit.

The sparks pass to earth through metal plates set in a trough of insulating material, which supports a motor-driven tape of standard 1-in. telegraph paper which is perforated and a permanent record on the tape is obtained.

The paper which is fed from a reel, passes along the trough and under two spring loaded guide rollers, one on each side of the driving wheel.

One train of sparks representing the time of injection, makes a straight line record along the tape owing to the sparking point being fixed.

The other train of sparks representing the time of explosion makes a wavy line record along the tape, since the sparking point is maintained in vibration at a predetermined frequency by means of a reed and an electro magnet in a low tension circuit.

By noting the number of oscillations in the ignition timing record which occur after the sparks have ceased in the injection timing record when both circuits have been broken, a time measurement of the ignition delay is obtained.

Fig. 6 shows a photograph of the complete apparatus.

Method of Operation.—The temperature of the vessel having been raised to the highest point which it is desired to investigate, the current is cut off and sufficient time allowed for temperature conditions to become stable. A charge of cold air is then drawn into the vessel by means of a vacuum pump, the scavenging and circulation of the air being assisted by means of the tangentially offset induction port. Sufficient time is then allowed to elapse for the air temperature, as read on a calibrated thermo-couple, to reach a maximum and commence to fall off. The fuel is then injected by means of the retractable injector nozzle, the time of injection and of the subsequent explosion being recorded electrically on the paper strip, the time reading being estimated by means of the tuning fork device. The temperature, and the time lag between injection and ignition, are noted on the record, and a further test carried out at a lower temperature, the products of combustion being first drawn away by means of the vacuum pump.

It will be noted that cold air entering the vessel passes across the thermo-couple and by this means the temperature recorded on the thermo-couple indicator is made to fall during the scavenging process, ensuring that in each reading no specially high localised heat has been absorbed in the thermo-couple fitting itself.

In this way a series of readings are taken every 20 or 30 degrees over a gradually falling temperature until finally, at the lowest temperature, no explosion occurs after an indefinite delay.

A complete calibration curve for any given fuel can be taken, when the fuel may be changed and a further series of readings taken with a different fuel.

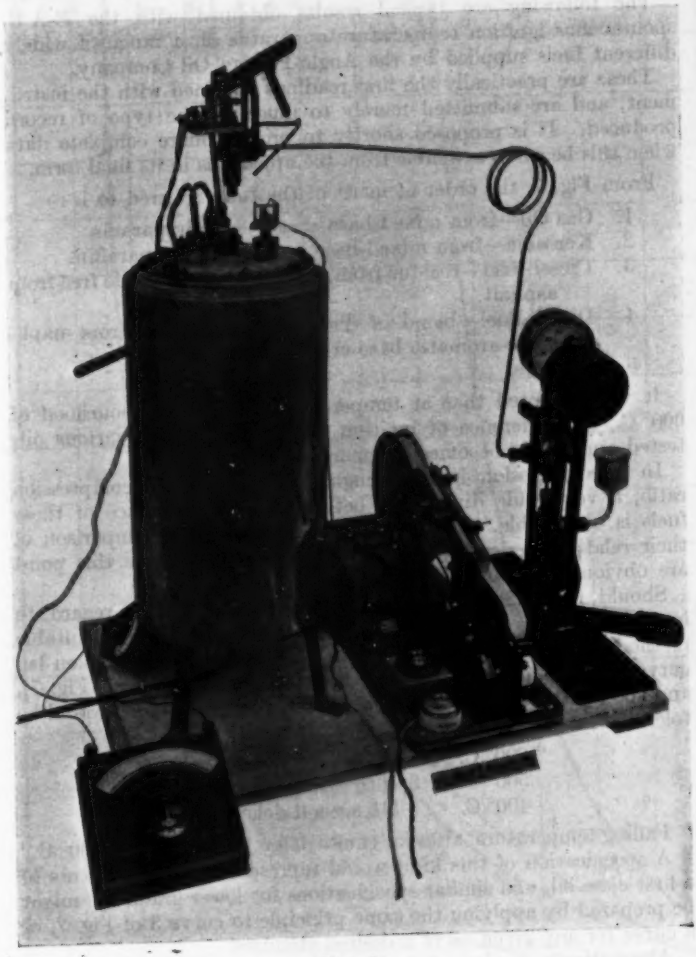


FIG. 6.

S.I.T. APPARATUS.

Preliminary Results with Various Fuels.

The following are typical results obtained with the R.A.E. spontaneous ignition temperature apparatus on a range of widely different fuels supplied by the Anglo-Persian Oil Company.

These are practically the first readings obtained with the instrument, and are submitted merely to illustrate the type of record produced. It is proposed shortly to provide more complete data when this becomes available from the apparatus in its final form.

From Fig. 7, the order of merit of the fuels referred to is :—

1. Gas Oil—from mixed-base crude—mainly paraffin.
2. Kerosine—from mixed-base crude—mainly paraffin.
3. Diesel Fuel—residue from naphthenic-base crude free from asphalt.
4. Diesel Fuel—blend of distillate and residue from naphthenic-aromatic base crude—mainly naphthenic.
5. Creosote.

It will be noted that at temperatures in the neighbourhood of 600° C., the difference of ignition delay between the various oils tested apparently becomes less marked.

In a compression ignition engine, even at 15 : 1 compression ratio, a very wide divergence between the performance of these fuels is observable, and thus for the purpose of a comparison of their relative merits in an engine, temperatures above this point are obviously not important.

Should it be desired to fix any specification with regard to ignition delay as recorded by this instrument, the most suitable method would appear to be to take as a standard the ignition lag curve of a first grade oil, such as Persian gas oil (curve 1, Fig. 7), and specify the limiting divergence from this curve which would be tolerated in any given fuel supplied. Thus :—

" 600° C. $<$ 1/5th second delay.
500° C. $<$ 3/10th second delay.
400° C. $<$ 4/5th second delay.

Failing temperature, after indefinite delay, not more than 350° C."

A specification of this kind would represent the requirements of a first class oil, and similar specifications for lower grade oils might be prepared by applying the same principle to curve 3 of Fig. 7, or a curve for any given oil of a desired standard.

Alternatively, in view of the inevitable variation in the properties of natural or distilled petroleum oils, it would be preferable to select as a standard some chemically pure organic substance (say, hexahydronaphthalene) which would serve as a fuel matching standard and also for calibration tests of individual instruments.

Ignition delay 1/5th second

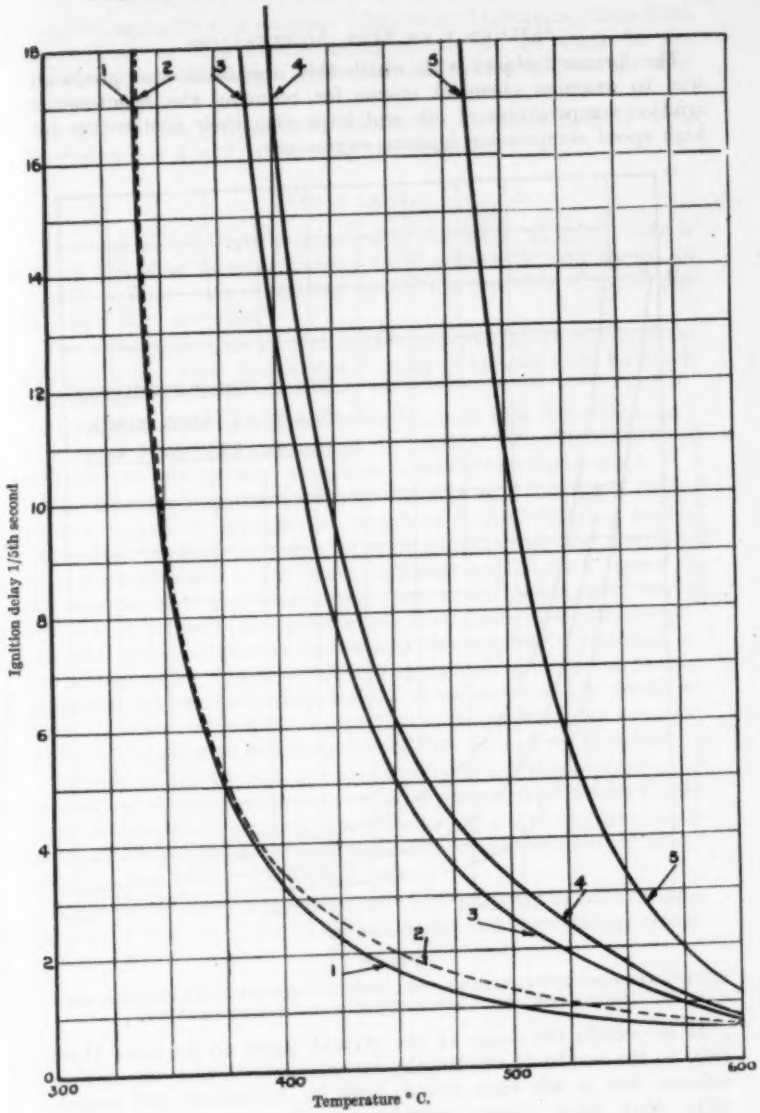

Ignition delay 1/5th second
18
16
14
12
10
8
6
4
2
0
300
400
500
600
Temperature ° C.
1
2
3
4
5

FIG. 7.

Influence of Fuel Accelerators.

The primary object with which this apparatus was produced was to examine chemical means for reducing the spontaneous ignition temperatures of oils and improving their combustion for high speed compression ignition engine use.

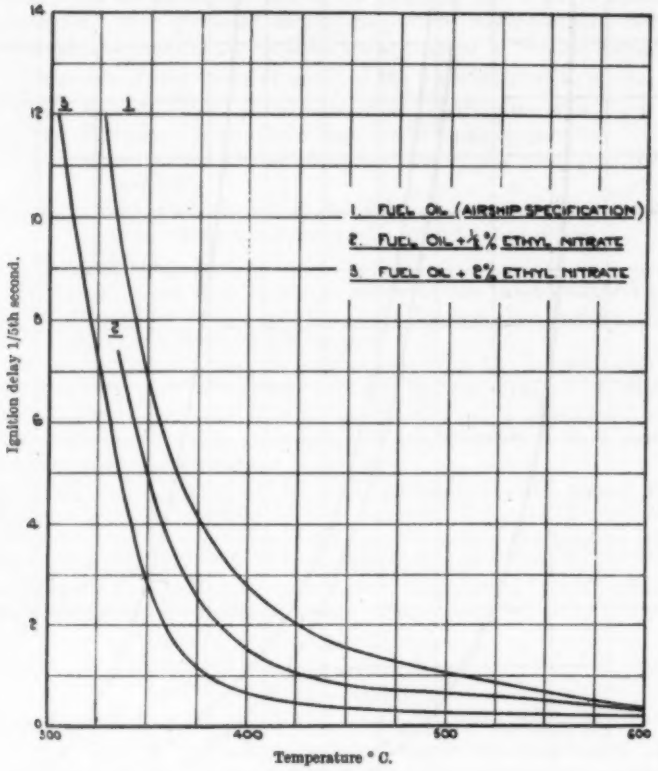


Fig. 8.

CURVES SHOWING THE EFFECT OF THE ADDITION OF ETHYL NITRATE TO A HIGH GRADE FUEL OIL. AIR MINISTRY AIRSHIP SPECIFICATION.

It is outside the scope of the present paper to do more than refer to the results of the lengthy investigation carried out on this subject, but it has been found, both by laboratory and engine tests, that ethyl nitrate provides an effective and practicable

chemical agent for this purpose. Engine and laboratory tests have shown that by this means improvement can be made in the performance, even of high grade fuel oils, whilst inferior oils may be regraded.

In Fig. 8 are given results obtained contemporaneously with those shown in Fig. 7, illustrating this effect.

Conclusions.

It is considered that the question of the S.I.T. of heavy fuels is one of the chief factors affecting their suitability with regard to smooth running, ease of starting, and the general life of the engine in which they are used.

The subject appears of comparable importance for compression ignition engine users to the knock rating of volatile fuels for spark fired engines.

It presents a problem no less complex than that of detonation—a problem which after more than ten years of intensive research is still without any absolute definition or means of measurement.

The best that has hitherto been done in this field is to devise various means of comparison which, although differing among themselves in absolute value, provide a method of fuel matching to a given standard. The same argument applies with regard to the estimation of the spontaneous ignition temperatures of heavy oils, which presents comparable physical difficulties and complications. For example, in the case of the apparatus discussed in the present paper, it is impossible to claim that in this or any other apparatus or engine absolute numerical values for S.I.T. could be given. On the other hand it should provide a reasonably accurate means for grading or matching heavy fuels to a given standard.

In view of the uncertainty existing regarding the properties of natural or distilled petroleum oils, a convenient standard fuel might be prepared by taking some chemically pure substance, such as hexahydronaphthalene, and adding to it a proportion of ethyl nitrate to bring it to a standard value.

Work is already in progress on this subject, as also is the question of comparing the S.I.T. results obtained from this apparatus with delay times recorded in direct engine tests.

Spontaneous Ignition Temperatures of Liquid Fuels and their Determination (German Investigations).

By J. L. CHALONER (Member).

INTRODUCTION.

RIEPPEL,[1] as one of the earliest research workers on the behaviour of different grades of liquid fuels in internal combustion engines, soon recognised that no relation existed between the flash point or burning point of a fuel oil and its ability to ignite spontaneously inside an engine cylinder, a characteristic or property depending primarily on its chemical character.

Holm investigated the ignition temperatures in oxygen by allowing oil globules to drop on to a porcelain crucible cover heated inside a vertical tube furnace swept through by a stream of oxygen. The temperatures were measured by a thermo-couple pyrometer. Holm published his first results in 1913.[2]

TABLE I.

	S.I.T. in Oxygen.
Tar Oil	530° C.
Benzene	520° C.
Ethyl Alcohol	510° C.
Hydrogen	470° C.
Petrol	415° C.
Lubricating Oil (Compressor)	410° C.
Kerosine (Petroleum)	380° C.
Rumanian Fuel Oil	380° C.
Kerosine (Lignite)	370° C.
Gas Oil	350° C.

Constam and Schlaefer continued the investigations by extensive experiments. Drops of oil were allowed to fall into a covered crucible raised to a definite temperature. The crucible was placed into another larger crucible; the space between the two crucibles was filled with ignited sand; an asbestos lid was fitted to prevent loss from radiation and other sources. Every precaution was thus taken to maintain a uniform temperature during the experiments. The temperature was measured by a thermo-couple suitably protected by a thin tube, and fixed at a distance of about 3 mm. above the base of the inner crucible. It was found that this distance of the thermo-couple had a material influence on the recorded ignition temperature. After preliminary experiments with an electrically heated crucible, the Bunsen burner was adopted. A slow stream of dry oxygen or air was allowed to pass into the

[1] Rieppel: *Z.d.V.D.I.*, vol. 51, 1907, p. 613.
[2] Holm: *Zeitschrift fur angewandte Chemie*, 1913, p. 273.

inner crucible. When working with oxygen, the ignition temperature was accompanied by a definite report, whereas when operating in an air stream there was just a slight puff audible.

The petroleum and lignite oils igniting at a lower temperature produced white vapours prior to ignition, whereas coal tar oils and tars which only become ignited at red heat, gave off darkish coloured vapours.

The oil drops vaporise prior to self-ignition. As long as the ignition temperature had not been reached, the paraffin-base petroleum oils and lignite tar oils vaporise without leaving any residue; asphalt petroleum oils, coal tar oils and tars on the other hand leave a cokey residue.

The influence of the material of the crucible on the spontaneous ignition temperature was also examined by using platinum, nickel, and porcelain crucibles of equal sizes.

Constam and Schlaepfer[3] were not in a position to judge whether Holm's apparatus gave greater accuracy. Their own apparatus was considered to be accurate within $\pm 30°$ C. (Table II.):—

TABLE II.

		Spontaneous Ignition Temperature. Constam and Schlaepfer.	
Grade of Fuel.	Holm.	Platinum Crucible Oxygen Stream.	Platinum Crucible Air Stream.
Gas Oil	350° C.	350° C.	400/460° C.
Coal Tar Oil ..	580° C.	550° C.	590/650° C.
Coal Tar	500° C.	480/530° C.	600/630° C.

Holm came to the conclusion that the spontaneous ignition temperature was a valuable addition to the knowledge of the suitability of fuel oils for Diesel engines. Constam and Schlaepfer did not share this opinion. They merely considered the results as a guide to the contention that already under atmospheric pressure and in an open vessel one could observe differences which the various grades of fuel oil would show as the result of their chemical character and when igniting in a Diesel engine operating under higher pressures.

Constam and Schlaepfer found confirmation of their opinion from a large number of ignition temperature measurements covering the gratest variety of fuels, ranging from Russian gas oils to heavy asphaltic Argentine crudes. Their deductions confirmed spontaneous ignition temperatures as inadequate for the determination of the suitability of fuel oils in engines. Definite deductions would have to be made from actual running tests in an oil engine.

[3] Constam und Schlaepfer: *Z.d.V.D.I.*, 1913, p. 1489.

The above considered opinions by recognised authorities evidently had considerable influence on further research work on ignition temperatures.

It was many years after that, at the instigation of Alt, further important experimental work was carried out in the Krupp laboratory.

At that time Alt[4] expressed the opinion that the question of the spontaneous ignition temperature is not merely to be looked upon as a criterion of the suitability of a fuel. If the temperature be the correct one, either by compression of by pre-heating the combustion air, injection air, or even of the fuel itself, or again by using an ignition fuel, then any fuel can be burnt, when the hydrogen content, the sulphur and the incombustible matter do not exceed a certain percentage.

It is much more important to know how the spontaneous ignition temperature is affected by the above mentioned influence in order to judge :—

(*a*) Under what heat conditions ignition can be positive for any given fuel under definite load conditions ;
(*b*) What should be the composition of fuels so that they ignite at the lowest possible compression and burn without residue ;
(*c*) Whether ignition oils are of use or necessary.

Wollers and Emkhe[5] published results with an ignition tester comprising an improved electrical furnace, an ignition block with a specially designed cavity, and an improved method of temperature measurement. These measurements, which were extended to oil vapours, showed relatively high spontaneous ignition temperatures for the various oil vapours, but found all the ignition temperatures more or less the same, although the origin of the oils was very different.

The conclusions drawn from these observations indicate firstly, that an experimental differentiation of the gasification and ignition phase did not bring about the desired explanation for the conditions obtained inside the oil engine cylinder ; and, secondly, that the more pertinent reasons for these unsatisfactory results are to be found in the great difference by which experimental conditions vary from practical conditions.

Recent German Types of S.I.T. Testers.

Enquiries made in various directions show that opinions are very divided on the utility of such a tester in general and on the merits of the few commercial types in particular. This attitude

[4] Alt : *Schiffbautechnische Gesellschaft*, 1920. *Z.d.V.D.I.*, vol. 67, 1923, p. 688.
[5] Wollers and Emkhe : *Krupp's Monatschaft*, Jan., 1921.

accounts for the limited extent to which the apparatus is used, and it will only be necessary to describe two types which have been developed on standardised lines.

1. *Krupp.*—The Krupp apparatus is designed as an electrical furnace either with chromium nickel for the heat agent and dealing with ignition temperatures up to 800° C. (Fig. 1) or with "Silit" Bars as heating agent for ignition temperatures over 800° C. up to 1300° C. (Fig. 2). The ignition block is of Krupp's rustless steel, provided with a conical shaped cavity which eliminates the other-

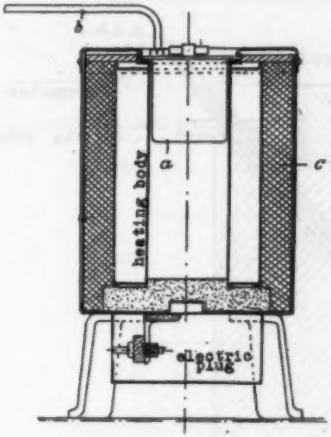


FIG. 1.

KRUPP ELECTRIC FURNACE WITH CHROMIUM NICKEL HEATING FOR IGNITION-BLOCK TEMPERATURES UP TO 800° C.

(a) Ignition Block.
(b) Oxygen Supply.
(c) Insulation.

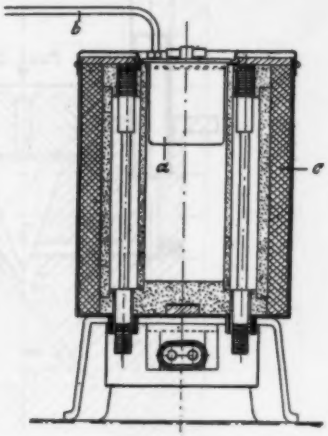


FIG. 2.

KRUPP ELECTRIC FURNACE WITH "SILIT" BAR HEATING FOR IGNITION TEMPERATURES BETWEEN 800° C. AND 1300° C.

(a) Ignition Block.
(b) Oxygen Supply.
(c) Insulation.

wise expensive platinum crucibles without in any way introducing catalytical influences on the ignition process. The oxygen supply is arranged for in a simple manner (Fig. 3). The ignition block is of such dimensions that the ignition space is heated in an absolutely uniform manner. The heat supply for the electric furnace is designed for various voltages, adjustable within very wide limits.

The ignition temperature of any liquid is ascertained by first of all running a trial test for the determination of the approximate ignition temperature of the fuel.

Under continuous maintenance of the oxygen supply, fuel is added in drops until same ignite with a definite report. From the momentary temperature of the ignition block and the temperature prevailing in the ignition zone ascertained by a second thermocouple, the ignition temperature is ascertained on the basis of established conversion calculations. The fluctuations in the

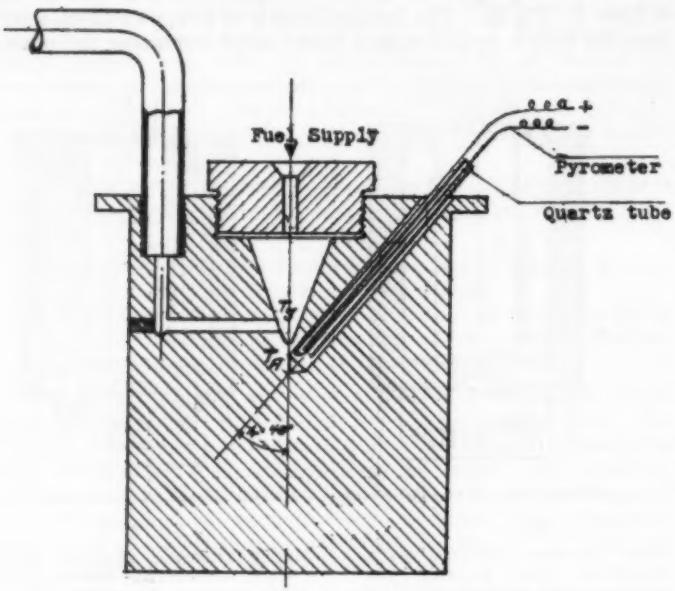


FIG. 3.

KRUPP IGNITION BLOCK.

experimental results are said to fall within 3–5° C. The tester is calibrated by first of all raising the internal temperature T_I up to 600° C. The electric circuit is then interrupted allowing the temperature to drop to 400° C. The circuit is switched in again, and two pyrometers are used to record simultaneously the internal temperature T_I and the external temperature T_A for the ignition block for every 10° C. temperature rise between 400° C. and 600° C. The resultant curve shows the correction which has to be applied to the ignition block reading T_A to determine the spontaneous ignition temperature (Fig. 4).

2. *Jentzsch* (Fig. 5).—This apparatus is also of the ignition block type with the crucible made of rustless steel situated in an electric furnace. The crucible has four pockets of equal size and arranged symmetrically. One of the chambers acts as a thermometer pocket, whilst the remaining three are used as ignition chambers. These may be looked upon as engine cylinders in which the compression temperature is provided by heating, the compression by the admission of oxygen, and the scavenging of the pockets

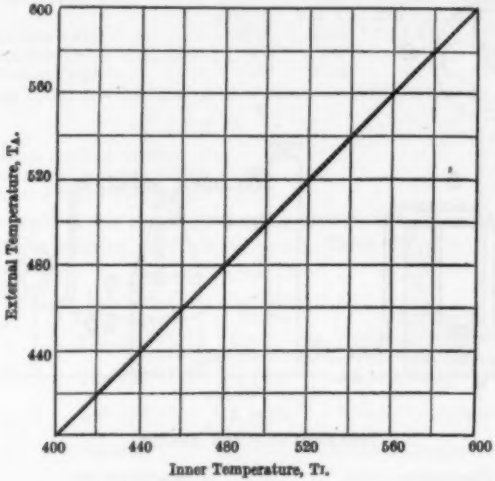


FIG. 4.

CALIBRATION OF THE KRUPP IGNITION TESTER.

$T_A = T_I$.
Correction = 0.

by means of an easily removable evaporation dish. Each of the three ignition chambers is fed with oxygen through a passage down the centre of the crucible extending at the bottom to three auxiliary channels, each of which leads to an ignition chamber. The oxygen is taken from an ordinary supply through a control valve, passed on its way through an oxygen bubble counter and a drier.

The Diesel cycle depends as much on the presence of oxygen as on the heat of compression. Jentzsch therefore contends that the number of oxygen bubbles corresponds to a definite oxygen density in the compression space of the engine.

The spontaneous ignition temperature is taken as the lowest temperature at which an oil drop will self-ignite in the presence of a rich oxygen stream. Jentzsch ascertained from a large number of tests that several substances may have the same self-ignition temperature, whereas the amount of oxygen required for ignition is in the ratio of 1 to 10. The inclination of all ignitable substances to ignite depends on the surface, temperature and amount of oxygen.

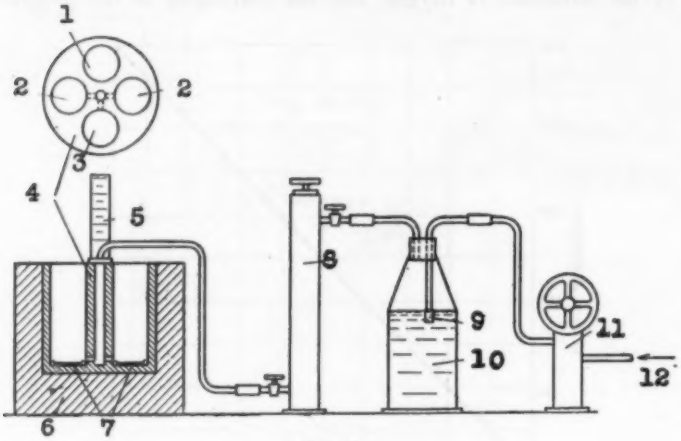


FIG. 5.

JENTZSCH IGNITION TESTER.

1. Thermometer pocket.
2. Auxiliary chamber.
3. Admission chamber.
4. Ignition crucible.
5. Thermometer.
6. Furnace.
7. Vaporisation dish.
8. Drier.
9. Jet.
10. Bubble counter.
11. Adjusting valve.
12. Oxygen supply.

The surface may always be brought to the same dimensions by using identical sizes of globules or equal quantities and so on. The ignition temperature, as determined in a rich oxygen stream, is more definite and subject to fewer mistakes than when using an air stream. The determination of the oxygen required by measuring the number of oxygen bubbles supplied per minute allows the calculation of the ignition value, which is a measure of the tendency to ignite, according to the following formula :—

$$z = \frac{t}{b + 1}$$

Z is the ignition value; t is the ignition temperature; b the number of oxygen bubbles per minute.

The character of the curves are illustrated in Fig. 6. Corresponding fuel properties being recorded in Table III.

TABLE III.

Fuel.	(1)	(2)	(3)	(4)	(5)
Sp. Gr. at 20° C.	0·86	0·78	0·87	0·84	0·94
Flash Point (P.M.)	74° C.	46° C.	68° C.	52° C.	78° C.
Distillation Tests—I.B.P. ..	158° C.	155° C.	178° C.	140° C.	178° C.
Up to 200° C.	8%	56%	12%	52%	4%
Up to 300° C.	78%	97·3%	96%	98%	45%
F.B.P.	360° C.	285° C.	213° C.	300° C.	370° C.
Net calorific Value, Kgs. ..	10,200	10,425	10,400	10,540	9,460
S.I.T.	265° C.	254° C.	276° C.	286° C.	290° C.
Lower Ignition Value	13·9°	10·1°	5·6°	4·7°	5·7°
Higher Ignition Value	550°	540°	540°	560°	560°
Ignition Value Factor	15°	11·4°	5·5°	4·5°	5·3°

Note.—The Ignition Value Factor is obtained from the following formula: —

$$\text{I.V.F.} = \frac{T-t}{b}$$

T = Higher ignition value.
t = Self-ignition temperature.
b = No. of oxygen bubbles per minute.

As a result of his investigations Jentzsch has tabulated ignition values for a number of fuels and oils, Table IV. :—

TABLE IV.

Fuel.	Ignition Temperature.	Ignition Value.	Application.
Petrol	270–300° C.	Up to 9° (at 300° C.).	Explosion Motor. 3 to 1 Compression Ratio.
Petrol (doped) .	270–315° C.	Up to 5° (at 300° C.).	4·5 to 1 Compression Ratio.
Petrol (doped) .	300–325° C.	Up to 3·5° (at 300° C.).	7 to 1 Compression Ratio.
Benzole ..	500–600° C.	Up to 6° (at 600° C.).	11 to 1 Compression Ratio.
Diesel Fuel ..	260–300° C.	50–80° (at 500° C.).	Airless Injection Diesel.
Diesel Fuel ..	260–300° C.	14–18° (at 500° C.).	Air Injection Diesel.
Diesel Fuel ..	260–300° C.	14–18° (at 500° C.).	Hot-bulb Engine.
Lubricating Oil	260–300° C.	Up to 5° (at 300° C.).	I.C. Engines and Low Pressure Compressors.
Lubricating Oil..	260–300° C.	Up to 2° (at 300° C.).	High Pressure Compressors and High Pressure Cylinders.
Switch Oil ..	250–280° C.	Up to 6° (at 300° C.).	Oil Switches and Transformers.
Fuel Oil ..	260–290° C.	As high as possible.	Marine Boilers.

The experience with highly volatile fuels, such as aviation spirits, indicates that, according to the Jentzsch formula, the lower ignition value should not be higher than 5°. This has been confirmed by comparative fuel tests with the ignition meter and in different engines on the test bench.

Schaepfer[6] has been analysing a large number of results obtained with a Jentzsch Ignition Tester. It has already been found by Jentzsch himself that ignition temperatures for the gases and vapours of liquid fuels heated in this ignition tester coincide with those of the liquid fuel drops themselves. This fact has been

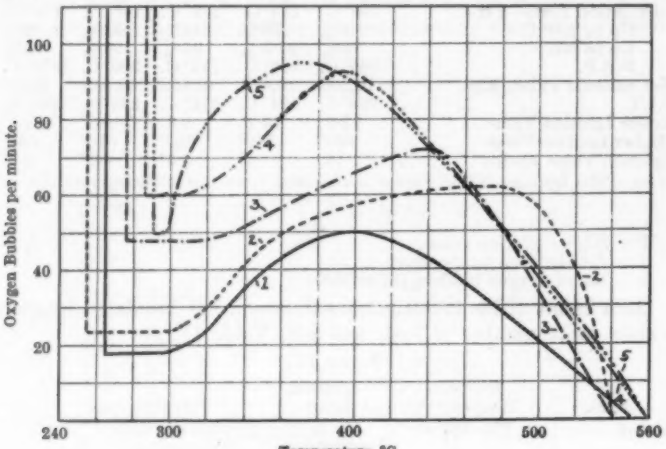


FIG. 6.

1. Russian Diesel Oil.
2. Rumanian Special Power Kerosine.
3. Gas Oil, origin unknown.
4. Gas Oil, origin unknown.
5. Lignite Fuel Oil.

taken as definite evidence that it is never a liquid which becomes ignited or burns, but always its respective vapour or gas. Although the relatively high oil vapour ignition temperatures have been taken as proof that the ignition for liquid fuels is not initiated by their oil vapours, the Jentzsch apparatus has provided evidence clearly supporting the contention that the ignition is initiated by the gas or vapour layer surrounding the heated fuel drop. Visible evidence of this procedure has been furnished by taking cinematographic records of the ignition phases for various fuels with and without oxygen stream (Figs. 7–10).

The first picture in Fig. 7 shows a drop of petrol in the brightly illuminated chamber of the crucible. The second, taken 0·0125 of a second later, shows ignition also in the auxiliary chamber,

[6] Schaepfer: *Schiffbautechnische Gesellschaft*, November, 1931.

which is not illuminated. The gases and vapours have thus become ignited by having found suitable ignition conditions in the adjoining chambers round about 300° C. and in the presence of oxygen. It appears that the ignitable gases and vapours formed

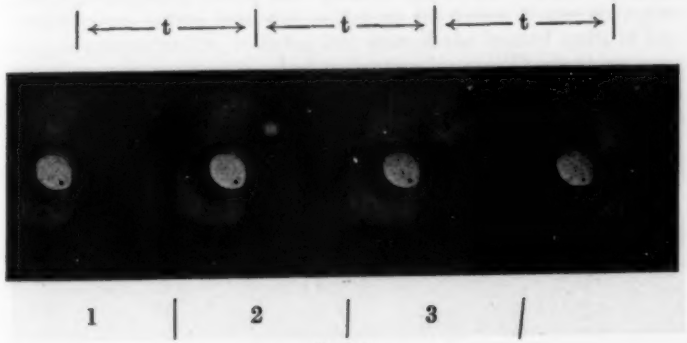


FIG. 7.

BEHAVIOUR OF A PETROL DROP AT 300° C. IN OXYGEN STREAM.
t = 0·125 sec. = 80 exposures per second.

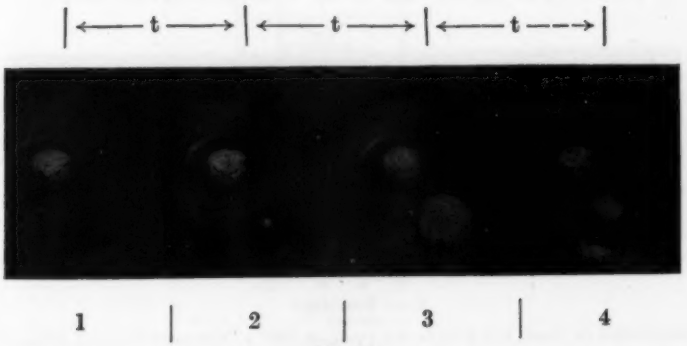


FIG. 8.

BEHAVIOUR OF GAS OIL DROP AT 300° C. IN OXYGEN STREAM.

initially have a considerable attraction towards oxygen, hence their tendency to move in that direction within the crucible. The fact that the ignition does not take place in the admission chamber is probably due to the rather rich mixture arising from vigorous vaporisation or gasification and thus not creating an ignitable

mixture. As a matter of fact, with the oxygen cut off and, therefore, only air present, the ignition invariably takes place in the ignition chamber and not in one of the auxiliary chambers. (Also see Fig. 9.)

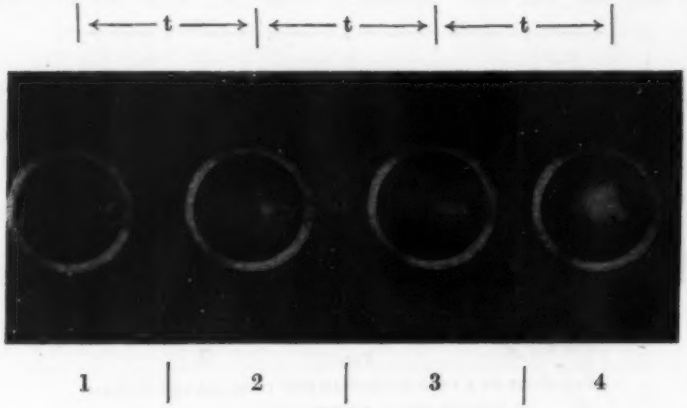


FIG. 9.

BEHAVIOUR OF GAS OIL DROP AT 600° C. WITHOUT OXYGEN STREAM.

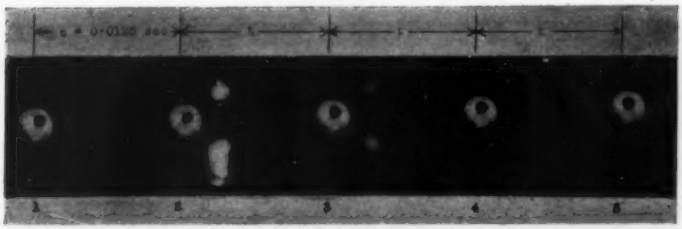


FIG. 10.

BEHAVIOUR OF COAL TAR DIESEL OIL DROP AT 600° C. WITHOUT OXYGEN STREAM.

Pictures 3 and 4 (Fig. 7) show the ignition initiated in the centre of the auxiliary chamber extending back to the admission chamber, whilst picture 4 also shows that gases or vapours have become ignited in the other auxiliary chamber. The petrol drop, however, remains in its position and is not at all affected by the ignition process. Fig. 8 shows a further set of pictures relating to gas oil. At 300° C. no drop is formed, presumably on account of the higher

distillation curve. The gas formation is not sufficiently vigorous to maintain the fuel drop in suspension, and as a result the oil spreads itself flat over the base of the illuminated ignition chamber, at the same time giving off gases and vapours. Here again picture 2 definitely shows that ignition commences in the auxiliary chamber and starts from the centre as the point of the strongest oxygen concentration, it being less around the heated walls of the chamber on account of the higher temperatures. The next picture, 3, taken 0·0125 of a second later, shows the ignition spread over the whole chamber, whilst picture 4 shows the ignition subsiding.

Fig. 9 shows the behaviour of a gas oil drop, but without the admission of oxygen, and therefore at the higher temperature of 600° C. The absence of the oxygen stream was responsible for no ignition in the auxiliary chambers. For purposes of comparison, Fig. 10 shows the behaviour of a coal tar Diesel oil drop, the ignition temperature also being 600° C. in this instance.

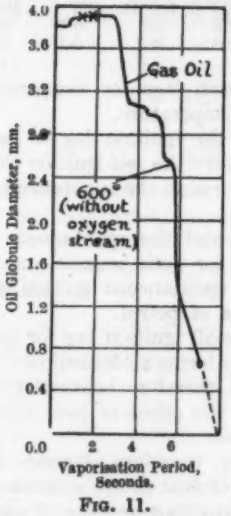


FIG. 11.

With the ignition initiated there was in no case any reduction in the volume of the liquid fuel.

In all tests the liquid fuel portion, whether in form of globules or speck, remained visible alongside or underneath the flame, quite unaffected by the ignition. After vaporisation or gasification down to a minimum size, this fuel particle would suddenly burst and disappear.

It has been said that the time element inside the engine is too short to permit any previous gas formation or vaporisation.

In this connection the Jentzsch instrument made it possible to measure the ignition lag which occurs between the drop reaching the ignition zone and the actual ignition, to observe the subsequent volumetric reduction in the size of the drop during vaporisation and gasification, and to record its total disappearance. The measurement of the volume reduction was facilitated because petrol and benzole drops take the shape of a spheroid on reaching the crucible cover raised to 300° C.; gas oil required 500° C. Fig. 11 gives such a curve for gas oil, and shows that the globule diameter does not diminish in a gradual but in a stepwise manner. It is probably true that the curve depends on the distillation characteristics of the liquid.

TABLE V.

Ignition Lag in Seconds.

	With 120 Oxygen Bubbles per min.				Without oxygen
	and 300° C.	400° C.	500° C.	500° C.	and 600° C.
Petrol	12·8	2·3	0·7	0·18	4·5 secs.
Gas Oil	2·0	0·3	0·1	0·08	1·2 „
Benzole	—	—	—	11.0	—

Table V. gives ignition lags for temperatures other than the spontaneous ignition temperature.

These figures show the ignition lag to be smaller the higher the temperature lies above the self-ignition temperature of the fuel, and to be a maximum around the spontaneous ignition temperature of the fuel.

The ignition lag around the spontaneous ignition temperature is very little different for both benzole and petrol, amounting to 1·8 secs., although the spontaneous ignition temperature of benzole lies 300° C. above that of petrol.

The exceptionally small ignition lag for gas oil is explained by the fact that gas oil only forms a " leidenfrost " globule at a temperature above 500° C. and, therefore, below 500° C. a very much larger surface is exposed to the effect of heat and oxygen than in the case of petrol or benzole.

The ignition velocity, therefore, depends very definitely on the temperature in excess of that of the spontaneous ignition temperature, the oxygen concentration and the oil gas or vapour formation. The effect of the oxygen concentration on the ignition velocities is shown by Table VI. :—

TABLE VI.

Ignition Lag (in seconds) at 500° C.

Oxygen Bubbles.	60 per min.	100 per min.	150 per min.	200 per min.	300 per min.
Petrol	1·95	1·8	1·5	0·6	0·2 sec.
70/30% Petrol/Benzole	2·85	2·3	2·1	1·0	0·57 „
50/50% Petrol/Benzole	No ignition.	3·0	2·6	2·2	0·9 „

The experimental figures, therefore, suggest that all other conditions equal, the ignition lag inside an engine decreases as the temperature in the combustion chamber or the compression increases.

The vaporisation velocity is influenced by actual temperature drop, heat conductivity, specific heat, heat of vaporisation, surface tension and actual surface.

Petrol and gas oil drops of about 3·5 mm. diameter vaporise or gasify at 300° C. within about 12 seconds, and at 600° C. in about 6 seconds.

The rate of vaporisation is approximately inversely proportionate to the cube of the globule diameter. When the globule diameter is reduced to about 0·3 mm. the acceleration in the rate increases so rapidly that the measuring time unit of 1–18 sec. is too long to permit following the process. As any oil gas formation liberates dissociation heat, the higher resultant temperature still further accelerates the process.

When injecting a fuel spray into an engine cylinder, the globule size is much smaller, and Schaepfer suggests the following vaporisation periods :—

TABLE VII.

Globule Diameter.	Vaporisation Period less than
0·1 mm.	0·02 seconds.
0·01 mm.	0·002 seconds.
0·001 mm.	0·0002 seconds.

It may well be considered, therefore, that vaporisation and gasification inside the engine is instantaneous, and hence even with high speed engines a few one-thousandths of a second suffice to prepare the fuel for the ignition and combustion stage by adequate vaporisation and gasification.

GENERAL CONSIDERATIONS.

The reason that the Continental types by ignition instruments are few in number is probably due to the fact that there is considerable variance of opinion regarding the practicability of spontaneous ignition temperatures as a fuel characteristic or criterion of its behaviour inside the engine.

The merits of the Jentzsch tester have been stressed merely because of the possibility in the variation of the oxygen supply, and the resultant range of spontaneous ignition temperatures for different oxygen concentrations. Again, the ignition lag is so easily ascertained with the use of cinematographic films.

Contrary to this contention, other German experts attach no importance to the ignition curve as obtained with the Jentzsch apparatus. The ignition point is very similar for a large variety of petroleum gas oils, so that any conclusions drawn as to their

relative merits are of very little practical value. As a matter of fact the opinion prevails that every grade of light Diesel fuel oil can be burnt satisfactorily even in a hot-bulb engine so long as the correct oil-air ratio is provided for.

There seems to be no generally accepted evidence that the spontaneous ignition temperature is any criterion to the behaviour of a fuel in an engine, with specific reference to the fuel knock. One reason for that discrepancy is no doubt due to the entirely different set of conditions under which the fuel charge burns in a combustion chamber of an engine and under which the oil globule evaporates on a crucible cover.

Reviewing, therefore, the position in general, it appears to be evident that opinion as to the ignition temperature as a measure of the suitability of fuel is very divided, which is again reflected in differences of opinions regarding the merit of the Jentzsch tester as the only developed type of spontaneous ignition meter.

Comparison of Spontaneous Ignition Temperatures and Starting and Ignition Delay Tests in Engines.

By L. J. Le Mesurier, M.I.N.A., M.Inst.Mar.Eng. (Member).

The two important respects in which the ignition quality of a fuel affects engine performance are :—

(*a*) *Ease of Starting.*—Depending on the lowest temperature at which a fuel will ignite with certainty at the compression pressure existing in the engine.

(*b*) *Running Smoothness.*—Depending on the time required *under running conditions* (when the engine temperatures are much higher than at starting) between the moment of injection of the first drops of fuel and the beginning of rapid pressure rise. The longer this period, in normal circumstances, the greater the running roughness and combustion shock.

An S.I.T. test should, preferably, be capable of supplying information regarding both these points; the apparatus required should be less expensive than an engine; and the time required for the tests should be less than if an engine is used.

Two methods of measurement of S.I.T. have been tried on a number of fuels, and the engine data under headings (*a*) and (*b*) determined by actual engine tests.

The methods of determining the S.I.T.'s were :—

(1) *The Moore Apparatus.*—Modified so that the oxygen supplied to the bomb was heated to bomb temperature before entering the explosion chamber.

(2) *The Farnboro' Apparatus.*—In the latter the fuel is sprayed into a large chamber of heated air at atmospheric pressure, and the delay before ignition measured by a pressure indicator, the moment of injection and the moment of ignition being recorded on a moving tape. The air temperature is controlled by a lagged heater element surrounding the chamber, and the fuel is sprayed from a standard fuel pump and spray valve.

Engine Starting Tests were made in a McLaren Benz single-cylinder engine as follows :—

The engine, which is of the prechamber type, and therefore requires the addition of heat for starting, is arranged with a water circulating pump driven from the flywheel and capable of a throughput of about 1500 gallons per hour when the engine is running at 300 r.p.m. Adjustment of jacket temperature is made by admitting either steam or cold water as necessary. An electrical heater is fitted into the inlet pipe, and a suitable controlling resistance is included in the circuit. The engine is direct coupled to a dynamometer which can be used to motor it steadily at any desired speed. The fuel pump is arranged with a two-way feed system for rapid change-over from one fuel to another, and a hand-operated vent valve is included in the spray valve body. The engine has a compression control lever working on the cam shaft which allows of running decompressed, at medium compression or at full compression. Shims may be removed from the foot of the connecting rod to alter the compression pressures if two pressure determinations do not suffice.

In order to carry out a series of starting tests the engine is first run under load for about half an hour to warm the lubricating oil. It is then motored at 300 r.p.m. with the spray valve vent open, and the jacket and air temperatures are adjusted to about 100° C. Compression is either full or medium according to the test required. An exhaust test cock immediately beyond the cylinder head exhaust flange is opened, and the fuel pump set to deliver full load fuel. On closing the vent valve on the spray valve a good fuel will fire immediately without smoke from the exhaust test cock. In such a case the jacket and air temperatures are reduced by about 10° C. and the test repeated, successive reductions of 10° being made in the temperatures until a misfire occurs, accompanied by a puff of white smoke at the exhaust test cock. The temperatures are then raised by 10° and the test repeated in falling stages of 1° until misfiring occurs. Finally, the temperatures are raised in 1° stages until a good start is obtained. (Air and jacket temperatures are always altered equally and to the same value.) In this way the minimum temperature of air and jacket for perfect starting at 300 r.p.m. is obtainable to within

± 1° C. for tests made on any given day, and to about ± 2° C. for tests made at long intervals. It is essential that the exhaust and inlet valves seat properly, and the spray valve must work without sticking or dribble. The arrangement is not ideal since the compression control lever only allows of two ratios being

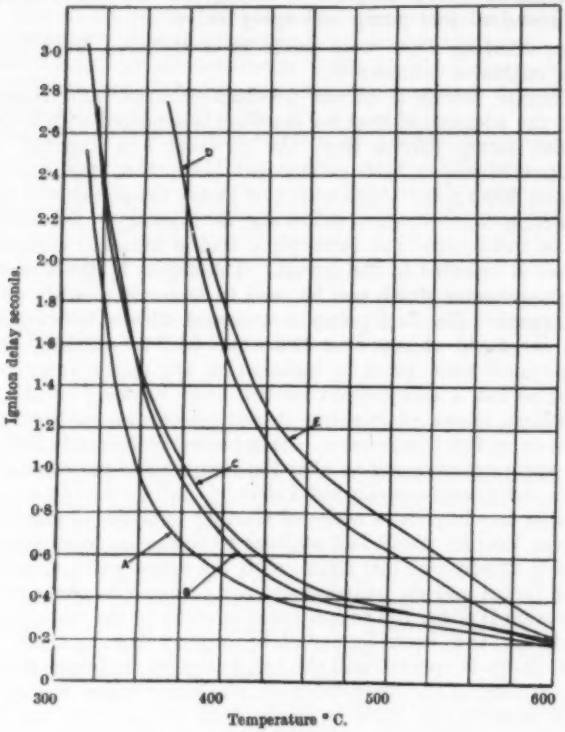


FIG. 1.

FARNBORO' S.I.T. APPARATUS TESTS.

used for a given ratio of prechamber to main cylinder air volume at the end of the stroke. Alteration of the two compression ratios by removal of connecting rod shims affects this air volume ratio, and thus the heat and pressure losses due to air flow from the main cylinder to the prechamber where the fuel ignites. It is not, therefore, possible exactly to correlate results obtained on more than two pressures.

Experience obtained with this engine indicates that there will be no difficulty in developing a direct injection engine for starting tests so that temperatures may be determined over a range of compression pressures at the rate of about one fuel per hour. With the existing engine, three fuels per day can be examined at four pressures. This is rather slower than the rate of test on the Farnboro' apparatus, which can handle four to five samples per day.

For the purpose of this paper five fuels were selected to include the normal range of oils available for Diesel engines, but excluding tar oils. Four of the fuels—(*a*), (*c*), (*d*) and (*e*)—were tested in the Moore apparatus, in the Farnboro' apparatus, in the McLaren Benz engine for starting, and in several engines for determination of the delay angle. The fifth fuel (*b*) was made by blending two of the others—(*a*) and (*e*)—to match a third (*c*) in the Benz engine. From other engine observations it was expected that the Farnboro' apparatus would show differences in delay with change of temperature between (*b*) and (*c*), and this expectation was realised.

The results are as follows :—

Moore Apparatus

Fuel.	Ignition Temp. °C. (in Oxygen).
(*a*)	262
(*b*)	—
(*c*)	261
(*d*)	279
(*e*)	273

Farnboro' Apparatus (in air).

The results of these tests are plotted in Fig. 1, ordinates representing degrees Centigrade, and abscissæ delay in seconds between moment of lift of spray valve and moment of pressure rise.

McLaren Benz Starting Tests.

Fig. 2 gives the engine starting results, air and jacket temperature as ordinates being plotted against compression pressure in the main cylinder. The low compression series is taken without shims, and the high compression series with shims, under the connecting rod. The full vertical lines represent the compression pressures with the engine running under full and medium compression obtained by the control lever. While the lines connecting temperature with pressure do not run continuously from the low pressure series (no shims under connecting rod) to the high, it is clear that similar tests made in an engine free from the disturbing influence of change of ratio of prechamber to main cylinder air volume would have given curves almost flat, and therefore simple

to take and to check compared with those from an apparatus giving results in the form of curves which change rapidly in slope from one condition to another.

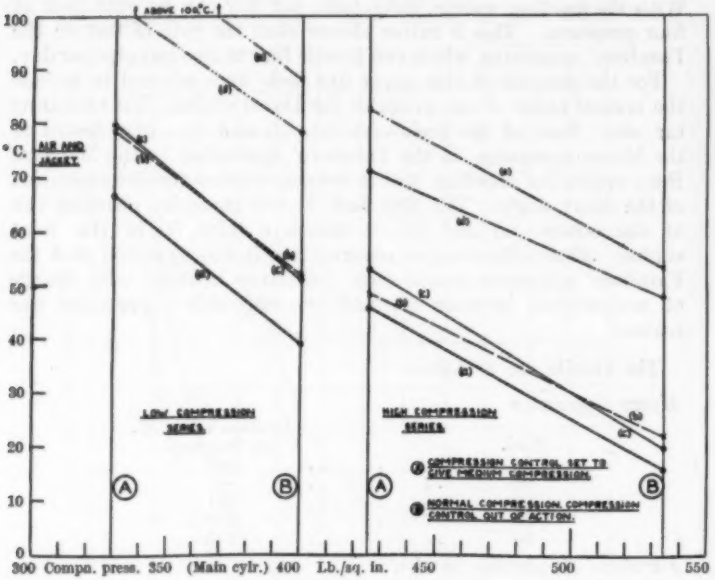


FIG. 2.

MACLAREN BENZ STARTING TESTS.

The nature of the discontinuity from one series of Benz tests to the other is consistent with the change of engine conditions, and it should be noted that fuels (*b*) and (*c*) cross in both cases, and also in the Farnboro' records.

Delay Angles measured in different types of engines.

Fuel.	Engine. Benz. 990 r.p.m.	Junkers. 1000 r.p.m.	Robey. 275 r.p.m.	Gardner. 1000 r.p.m.	Petter. 625 r.p.m.
(*a*)	2°	10°	8°	8°	37°
(*c*)	3	11	8	12	51
(*d*)	7	15	10	16	52
(*e*)	7	15	10	19	53

When three fuels (*a*), (*c*) and (*e*) were tested in the Gardner engine for delay with the compression pressure reduced in stages by throttling, it was found that (*c*) had a delay nearly as small

as (*a*) at full throttle, but that the delay increased rapidly with fall of pressure until it was nearly as long as that for (*e*) at low pressures.

The Admiralty has supplied the following information on trials carried out in an Air Injection and a Solid Injection engine :—

(1) *Air Injection.*—Single-cylinder, 4-stroke, single-acting, 9 in. dia. × 12½ in. stroke, developing 30 B.H.P. at 375 r.p.m., compression pressure 500 lb./sq. ins.

(2) *Solid Injection.* — Single-Cylinder, 4-stroke, single-acting, 14½ in. dia. × 15 in. stroke, developing 100 B.H.P. at 380 r.p.m., compression pressure 465 lb./sq. ins.

In all cases the engines were started on Shale Oil and turned over to the fuel under test when running. The S.I.T. was ascertained in each case by means of a Moore Apparatus using oxygen.

The results are summarised as follows :—

Fuel.	Gross C.V. in B.T.Us.	S.I.T.	Remarks.
1. Oil produced by hydrogenation.	18,840	288° C.	Ran satisfactorily with slight modification to spraying conditions in blast and solid injection engines, but it was possible, though undesirable owing to detonation, to run the engines without modification.
2. Oil produced by Low Temp. Carbonisation of Cannel Coal.	18,250	300° C.	As above.
3. Oil produced by Low Temp. Carbonisation of Bituminous Coal.	16,780	414° C.	Engine of blast type would not run with more than 40% of coal oil mixed with 60% shale owing to heavy detonations. Satisfactory running obtained by modification of atomising ring.
4. Creosote ..	16,900	466° C.	Satisfactory running not obtained due to detonation and misfiring after turning over from shale. After a short period engine stopped.
For Comparison.			
1. Persian Fuel Oil	19,060	268° C.	—
2. Trinidad Fuel Oil	18,800	279° C.	—

These results refer to fuels of widely differing S.I.T. and merely indicate a tendency towards erratic running and combustion shock with increase of S.I.T.

Conclusions.

It is clear that S.I.T. tests made on apparatus such as the Moore are almost useless. They serve only to distinguish very high S.I.T.'s from very low, although they might be improved if a time factor could be introduced. The Farnboro' apparatus includes measurement of the time factor and the results are much more interesting and valuable. It grades the selected fuels, generally, in the same order as the engine as regards starting properties, and curves (*b*) and (*c*) show crossings comparable with those obtained from the engine starting tests. There is not, however, any sign of (*c*) leaving (*a*) by an amount necessary to make it almost identical with (*e*), although this behaviour has been observed in the change of delay on these fuels between low and high compression engines.

It will be noted from the table of delay angles given that (*c*) is the most affected by change of engine type.

The inference is that the Farnboro' apparatus is of definite value for determination of ease of starting, but that, at present, it does not give data which can be correlated with delay angle under running conditions in all cases. A good starting fuel is always a smooth running fuel, but the converse is not always true. A fuel with bad starting qualities may also give smooth running, for example, Fuel (*c*) which has good starting qualities, has a delay period in the Petter engine almost equal to Fuel (*e*).

The design of a special test unit should not present any difficulties to-day provided it is made sufficiently flexible in its range of adjustments. The C.F.R. engine is finding an application for this class of work in America, but the cylinder dimensions are on the small side in comparison with high-speed Diesel engines, and there are many obvious compromises which could be eliminated if a special plant were evolved. The development of the technique of gasoline testing in engines is known, now, to have suffered considerably from attempts at too great a simplification of test conditions and technique, but these attempts were excusable—in fact, almost inevitable—in view of the novelty of the problem. There will be less excuse if the experience gained during the last ten to twelve years in gasoline testing is overlooked in the development of methods for testing Diesel fuels. It is known that the behaviour of two gasolines may be the same in one engine but different in another as regards anti-knock rating, and there is no reason to expect more consistency with fuel oils. The best procedure seems to be to develop a flexible design of testing unit, and to explore its behaviour under all possible conditions until sufficient data has accumulated to secure results comparable with

those from engines used commercially, and then, if necessary, to standardise more than one set of test conditions so that each broad class of commercial engine may be covered.

Practical necessity has forced, not only the adoption of an engine for gasoline testing, but also the use of different technique for the testing of aero engine grades from that applied to automobile grades, and there are indications that further modifications are required to bring laboratory results into better agreement with road behaviour.

Too early an attempt to simplify the testing of heavy oils must therefore be regarded with suspicion, for the same, or a greater, order of difference exists in the application of Diesel fuels, and the sooner these differences are generally understood and accepted as important, the sooner will a satisfactory testing unit and test methods be possible.

The Author wishes to express his thanks to the Admiralty, Air Ministry, and Staff of the Anglo-Persian Oil Company Research Laboratory at Sunbury, for allowing him to quote the results of their investigations on this subject.

Ignition Quality of Diesel Fuels.

By J. J. Broeze.

While engaged in Diesel engine research work the need of a simple method for measuring the ignition quality of Diesel fuels was found. This method should give a better understanding of the behaviour of these fuels in a series of test engines and eventually serve as a general method for checking the quality of commercial fuels.

It has been understood that determination of the spontaneous ignition temperature alone gives no reliable results. Measurement of delay periods appears to be necessary, and this should be done in as simple a way as possible. The new R.A.E. apparatus, as described by Mr. Foord, is undoubtedly an advance in this direction.

The method used in the engine testing laboratory of the Bataafsche Petroleum Maatschappij at Delft, working on engine diagrams, has been published.[1] This method consists of taking time diagrams on an engine at normal air induction and while throttling, and has been extended to making measurements at different compression ratios. Thus, with a constant rate of injection, fuel behaviour could be studied under widely varying engine conditions.

[1] *Engineering*, 1931, **132**, 603–606, 687–689, 755–756; *J.I.P.T.*, 1931, 17, 73A–74A.

Recently the need for reading ignition lags without the necessity of doing sensitive measuring work on diagrams has arisen, and an instrument for direct indication of the lag has been designed. This instrument (Fig. 1) is called an inertia lagmeter,

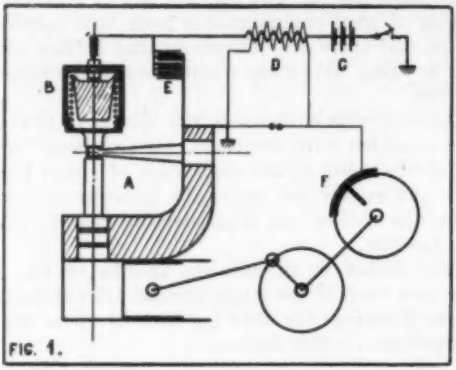


FIG. 1.

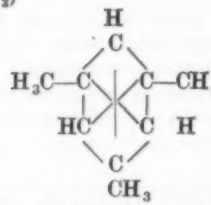
and consists of a sprung inert mass connected to a pressure indicator. This inert mass breaks an electric contact at the very moment that a rapid pressure rise sets in, and such independently of the pressure at that moment. The delay may thus be recorded on a diagram or may be made visible by means of a neon tube spark indicator.

It should be generally appreciated that for the calibration of any ignition testing apparatus, reference fuels are needed if a high degree of accuracy is desired. Mr. Foord has already stressed this point in connection with the R.A.E. apparatus. As described in the above-mentioned paper, cetene ($C_{16}H_{32}$)

$$CH_3—(CH_2)_{13}—CH=CH_2$$

(Sp. gr. 0·788 ; b. pt. 274° C.=525° F.)

was chosen as a standard for high ignition quality, and mesitylene (C_9H_{12})



(Sp. gr. 0·863; b. pt. 164·6° C.=329°F.)

as a standard for low ignition quality.

Ignition qualities have been expressed in blends of these two standards; thus all fuels examined have obtained their own "*Cetene Number*," quite comparable to the "Octane Number" for gasolines. For routine work, two inexpensive sub-standard fuels, a gas oil and an Edeleanu extract, are used.

So far discrepancies in rating of fuels under different conditions in the test engine have been so small that the measurements at 30 atmospheres compression serve with sufficient accuracy for the rating test. Only fuels of extremely high boiling range (400° to 500° C.) appear to make differences of importance.

For commercial fuels, of which some hundreds have been studied, the cetene number ranges between about 35 and 70.

High-speed engines and particularly some super-sensitive types may require cetene numbers of over 60, and may even then be capable of improvement by the use of dope, whilst many slow-speed engines run well on fuels of 35 cetene number or even less.

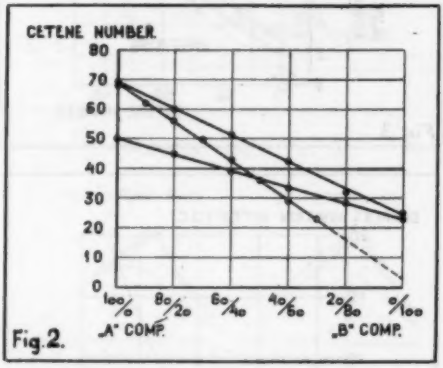


Fig. 2.

An important fact of much use in blending fuels from components of different cetene number is that cetene numbers for blends follow very closely a linear relationship, so that the quality of blends can be controlled with a high degree of accuracy. Fig. 2 shows three such blending tests, in which three different gas oils ("A" components) have been blended with two different Edeleanu extracts and with a coal tar oil ("B" components) respectively.

Before adopting a standard rating method it was necessary to determine that discrepancies between results obtained on different types of engines are rather unimportant. Figs. 3, 4 and 5 illustrate this fact for three engine types.

Fig. 3 shows the advance of injection necessary to avoid misfiring in a Deutz high-speed antechamber engine for fuels of different cetene number. The width of the band between the dotted lines corresponds with the experimental error on that engine as found by repeat tests.

Fig. 4 shows time of ignition in a Thomassen-Ricardo sleeve engine against the cetene numbers of the fuels used.

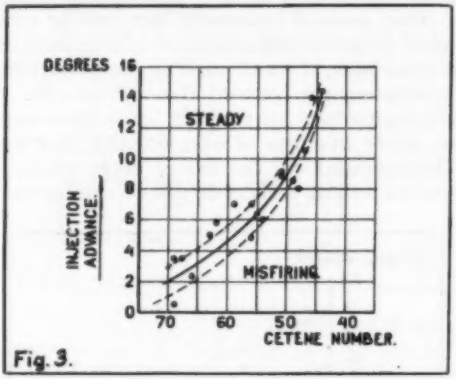


Fig. 3.

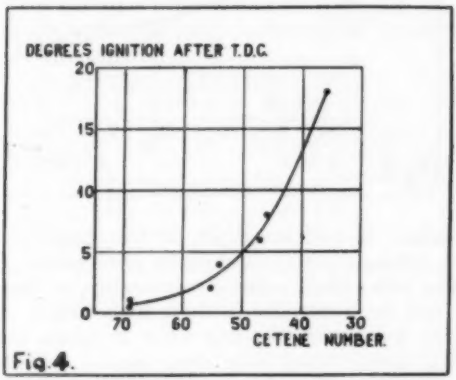


Fig. 4.

Fig. 5 shows the relation between the amounts of ethyl nitrate that had to be added to a fuel to insure regular running in a Gardner hot bulb engine, and the cetene numbers of these fuels.

From the information and experience obtained it is assumed that there is really one factor that controls the ignition quality

of Diesel fuels, and that is the thermal stability of its molecules. Stress should be laid, however, on the inherent difference between the pure ignition quality of a fuel and its behaviour in different engines. In special cases engine characteristics may cause what seem to be anomalies, of which some instances are given.

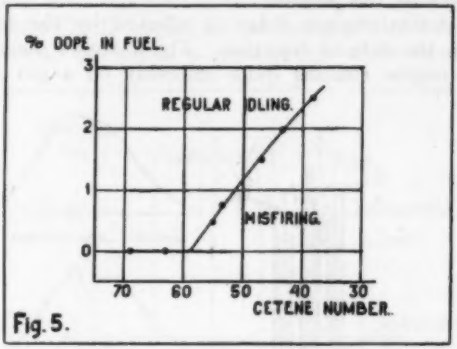


Fig. 5.

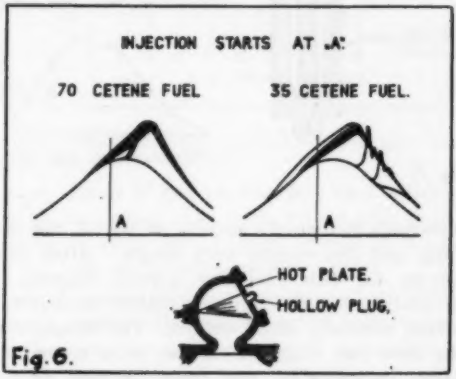


Fig. 6.

A Kromhout-Akroyd type engine was found to be running equally well on fuels of almost any cetene number. On analysing this behaviour it was found that combustion was already visible on the diagram at such a piston position that injection had not yet begun (Fig. 6). Combustion at such a moment could therefore only be ascribed to fuel remaining from the previous cycle, doubtlessly in some unscavenged corner. This fuel apparently inflames again during compression and ignites the fresh charge. It often

has appeared that this flame ignition is more efficient with a fuel of low cetene number than with one of high cetene number, so that the engine would run smoother on the fuel with the lower cetene number. This type of engine often causes problems, as is well known, and too much stress should not be laid on them as fuel remnants confuse the problem.

In air-injection engines delay is affected by the influence of viscosity on the rate of injection. Fig. 7 shows diagrams of a Werkspoor engine running quite smoothly on a gas oil. On a

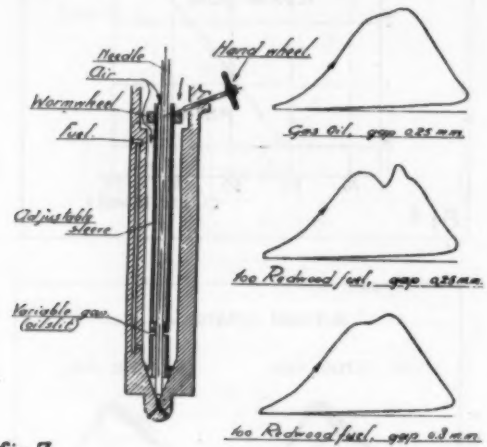


Fig. 7.

fuel of 100 seconds Redwood viscosity at 100° F. the delay became seriously long and the engine very rough. After correcting the injector setting for this fuel the normal diagram reappeared. Under test conditions, this engine is rather insensitive to ignition quality, having normally small delays. The discrepancy observed between the first two diagrams is due to a secondary influence, viz., a change in viscosity, and must be seen as a mechanical problem relating to mixture formation and unconnected with ignition quality.

The measurements of ignition quality are made in a solid injection engine which, due to its mechanically controlled injection, is insensitive as to viscosity as regards rate of injection, and has shown (Fig. 8) no appreciable influence of changes in viscosity, as caused by preheating of the fuel, on ignition up to 145 c.p. (600 secs. Redwood I.). This limit of viscosity was

apparently reached by Fuel 4 in Fig. 8 at 50° C., the viscosities of the other fuels tested ranging from 0·8 c.p. at 100° C. to 45 c.p. at 20° C., which are practically limit figures for normal Diesel fuels.

It will be interesting to obtain results on the R.A.E. apparatus in correlation with observed cetene numbers.

The modified C.F.R. engine for the rating of Diesel fuels is under observation with the aid of a combination of the inertia lagmeter

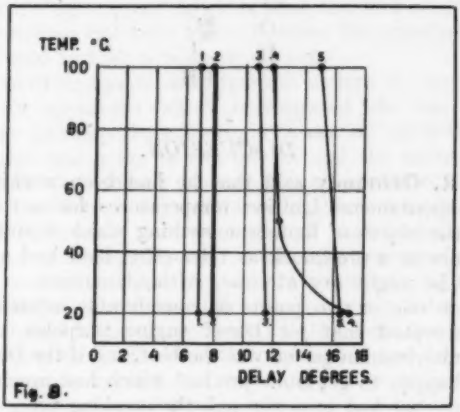


Fig. 8.

and a neon tube spark indicator, which would give an extremely simple routine test.

In conclusion, stress is laid on the fact that although ignition quality plays an important role, fuels with a high ignition quality will not improve the efficiency of Diesel engines in the same way as high anti-knock fuels do for the gasoline engine.

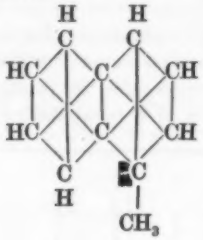
Sensitiveness of engines, which necessitates a high ignition quality, i.e., special fuels, restricts the general use of such engines.

Already a few engine designers have succeeded in building engines that are largely indifferent to ignition quality, and the trend of future development of the Diesel engine is tending in the direction of the " omnivorous " engine.

Once this principle is generally accepted by engine designers, the oil supplier's task will be to supply fuels of reasonable ignition quality giving a clean burning and a minimum cylinder wear.

Appendix : In view of the high cost and of the low boiling point of mesitylene, a change has been made to α-methyl-naphthalene as a low standard substance. This substance ignites only slightly

better than mesitylene, and has the following characteristics: Formula, $C_{11}H_{10}$; sp. gr. 1·01; b. pt., 242° C. (468° F.); m. pt., —22° C. (—8° F.); structure,



DISCUSSION.

Dr. W. R. Ormandy said that he had been working on the subject of spontaneous ignition temperatures for a considerable time with the object of finding something which would have the same influence as a pro-knock as tetra-ethyl lead had as an anti-knock, and he might say at once, without success.

There were one or two points of considerable interest. It was generally accepted that for Diesel engine purposes a straight-distilled Pennsylvanian gas oil was the best, and if the Diesel engine owner did happen to get some product which had much the same Engler curve, but had been through the cracking process once, he discovered that it did not work as well. Did the fuel injected into the Diesel engine burn as a liquid? He thought not; it burned in the vapour form. But was it the evaporated oil or was it the product of the cracking which had taken place? It would be found, he thought, that those oils which were good for starting and smooth running in the Diesel engine were the same oils which were satisfactory from the gas works' point of view for enriching purposes. An oil was wanted which would give the highest number of B.Th.U. in a gas form when the oil was cracked under the most advantageous conditions appertaining to that type of work. A great deal of work on the behaviour of these types of paraffin oils—gas oils—had been carried out, for instance, by the Gas Light and Coke Company, and it would be interesting if there was any parallel between the results which would enable one to form a picture as to the probable behaviour of Diesel oil.

If in fact an oil which was injected as a fine spray into a heated space in the Diesel engine was cracked, it was converted into lighter portions and heavier portions, and from what was known of the behaviour of the low-boiling hydrocarbons, that they had a

comparatively high spontaneous ignition temperature, and the heavy tail ends had a much lower spontaneous ignition temperature, then cracking might be advantageous. That was why it was desired to use oils which cracked readily, in that a heavy tail was forthcoming which ignited at a much lower temperature and burned much more easily than the lighter portions and the permanent gases. It would be exceedingly interesting to have something in the nature of a Ricardo Diesel engine, a variable compression engine run with various fuels, supplied with nitrogen instead of air or oxygen, in order that the fact could be settled whether cracking did take place, because the examination of the tail gas would furnish a positive answer.

With regard to spontaneous ignition meters, he was very much against any apparatus which necessitated the use of oxygen. He thought that experiments should be carried out with air, as the Diesel engine was going to run on air, and the assumption could not be drawn that merely because the air contained 20 per cent. of oxygen, therefore, if oxygen was used, it was five times as active. From the old records it could be found that certain substances, when tested with oxygen, had certain spontaneous ignition temperatures, and with air, perhaps 80 or 100 degrees higher, but also other substances where the difference was only 5 or 10 degrees, and some in which the temperature was the same in oxygen and in air. This pointed to the fact that one could not rely on results from experiments carried out with oxygen as indicative of the behaviour of the same substances with air.

He would point out also that tetra-ethyl lead, when added to a fuel to be tested in the spontaneous ignition meter, should send the spontaneous ignition temperature up, and it certainly did with air, but had no effect whatever with oxygen. He had published the results of the action of tetra-ethyl lead on various substances, and had been exceedingly disappointed to find that it had no effect, but Egerton, of Oxford, had repeated the work, using air, and had discovered that the result obtained was that which would be expected, having regard to the action of tetra-ethyl lead in practice.

With regard to the Moore type of meters, he would admit at once that the Farnborough instrument was a vast improvement, and enabled one to do a lot of things the Moore meter would not do. But he must say that the results given by Mr. Le Mesurier did not, in his opinion, very strongly bear out his contention that the Moore meter did not convey information of value. It would be noticed in Fig. 1 of Mr. Le Mesurier's paper that A, B and C, were close together and E was a long way off, but if one looked at the top of the diagram, where the spontaneous ignition temperature

after a long lapse of time was given, it would be found that the relative position of the lines A, B and C close together and E a long way off was pretty much what would be expected, that the differences were nearly as pronounced up there as they were lower down, and the deductions which were drawn from these differences seemed to be hardly justified.

He pointed out that the weak point of the Moore apparatus lay in the fact that the oxygen contents of the crucible were not sufficient to burn more than one half of the organic material contained in the drop. He favoured the use of a larger bulb in a fusible metal bath, but even then the contents of the bulb were not sufficient when working with air.

Mr. R. Stansfield said that with regard to Mr. Chaloner's paper, he noticed that it was stated that ignition never occurred in the liquid itself, but always in the vapour from the drop. The speaker thought it might be worth referring, in connection with this statement, to the conclusions which had been reached by various experimenters working with engines. The experiments suggested that volatility had little or no influence on delay, and this had sometimes been misinterpreted as meaning that ignition took place in the liquid. The photographs of combustion in the Jentzsch apparatus showed that burning was well established long before any appreciable diminution of drop size occurred, and it seemed probable that the end of delay in an engine was reached similarly, while the greater part of the fuel was still in the liquid state. It was thus possible to reconcile ignition from vapour on or near the drop surface with the fact that the amount vaporised needed only to be extremely small.

It had been shown experimentally that a heavy lubricating oil and a gas oil from the same crude had very nearly the same delay, and yet the former did not begin to distil until a temperature of 360° C. was reached at atmospheric pressure, while the latter was completely distilled at that temperature. When a gas oil from a crude of different chemical nature, but of the same volatility as the other gas oil, was examined, the delay was nearly double. Evidence of this description indicated that the chemical character of the fuel, rather than its volatility, determined delay, and that the amount of vaporisation necessary for ignition to commence was of small delay.

In Mr. Foord's paper the curves in Fig. 7 showed that ignition would occur with all the fuels at a suitable temperature with a delay as long as 3.6 sec. In Fig. 1 of Mr. Le Mesurier's paper, all the curves finished below the 3.6 sec. line. Fuel A finished at 2.6 sec. and fuel C at 3 sec. It would be interesting to know

whether it was possible to determine, with any precision, the limiting point above which no ignition occurred in an indefinite time. Perhaps the curves rose too steeply for this to be done.

There were indications from engine tests that, once some fuels started to react before ignition, the reactions continued with progressive lowering of the S.I.T. even though the surrounding temperature began to fall. Other fuels needed to be maintained for a time above a certain temperature or the ignition never occurred. Two such fuels might have the same starting properties and the same smoothness under running conditions at full compression, but one might fail if the compression were reduced by altitude, while the other might still ignite satisfactorily.

With regard to dope effects, the speaker thought that the R.A.E. apparatus was exaggerating their value. One-half per cent. of ethyl nitrate, according to Fig. 8, reduced delay by about 50 per cent., and 2 per cent. of dope reduced it by about 75 per cent. from the values for the untreated fuel. In various engines which he had examined the reduction in delay was only of the order of 25 per cent. for 2 per cent. of dope in a very good fuel of the same order as that selected for Fig. 8. Even in a poor fuel the reduction in delay with 2 per cent. dope was only about 36 per cent. It was known that the effect of ethyl nitrate was more pronounced when it was used in the vapour form in the engine inlet than when used mixed with the fuel itself, and it occurred to him that possibly the time element in the R.A.E. apparatus was so long that a fractional distillation effect existed to a much greater extent than in an engine. If this were the explanation of the differences, then it seemed possible that the ignition of undoped fuels might also be affected more by volatility in the bomb tests than in an actual engine.

With reference to Mr. Broeze's paper, he would like to congratulate him on the ignition lag indicator. This should be an admirable instrument for high-speed engines, or for any design in which the pressure rise was really rapid. It would fail in certain slow-speed engines where the rate of rise never exceeded the steepest part of the compression line. It was true that shock was rarely commented on in such low rates of pressure rise, although it was easily possible to detect by ear the difference in noise caused by as little as 2 degrees difference in delay.

He would like to know whether the use of cetene and mesitylene as standards was liable to lead to trouble on account of viscosity. The spray penetration and spread of blends of these substances must be appreciably different from the average Diesel fuel, and it might be found that viscosity was a factor which would lead to wide divergencies in fuel ratings, depending on the engine in which

the tests were made. The same sort of objection applied to the octane/heptane scale for heavy oils. He was not able to make any constructive suggestions as regards standards, but suggested that caution should be observed and a more searching series of tests made before a definite decision was reached on the reference fuels. If possible, the viscosity of the standards should be of the same order as an average high-speed engine fuel to ensure the minimum deviation between ratings in different engines.

Mr. C. B. Dicksee said that Mr. Foord had stated that at temperatures in the neighbourhood of 600° the difference of ignition delay between the various oils tested apparently became less marked, and he suggested that under those conditions it was not very important. Actually, in high-speed engines, compression temperatures of the order of 600° C. and above could be, and were, obtained, and there was a marked difference in the behaviour of the different fuels. Cases had been found of a fuel which gave unsatisfactory running, although the ignition point was only a few degress above that of a fuel which gave entirely satisfactory results. Lowering the ignition point by the addition of ethyl nitrate produced a considerable improvement, but in some instances the performances were not equal, although the ignition temperature had been brought to a figure below that of the satisfactory fuel. That went to prove that ignition temperature alone was not the governing factor, but had to be taken into consideration with other factors, such as the crude from which the fuel was obtained, and other physical properties.

As far as one could tell from testing a large number of fuels, the distillation curve and the ignition point seemed to give the most satisfactory indication as to suitability or otherwise. No doubt some method would be devised which would give more conclusive results, but so far those two enabled one to give the nearest guess to the results which would be given by the engine.

Mr. Chaloner, in Table VII., quoted sundry vaporisation times. These entirely omitted any question of pressure effect, and pressure effect must be quite considerable under the conditions which existed in compression ignition engines, so that to argue that the vaporisation was instantaneous in the engine, he thought, was going a little too far. He did not know whether that was Mr. Chaloner's own deduction or that of the other experimenters whose work he was discussing.

The statement quoted by Mr. Chaloner that the opinion prevailed that every grade of light Diesel fuel oil could be burned satisfactorily, even in a hot bulb engine so long as the correct oil-air ratio was provided for, suggested that the author of that

remark had not had much experience of a wide range of fuels with different engines, because what he stated was, emphatically, not the case.

Mr. Le Mesurier had discussed the delay angles for different types of engines, using the same series of fuels, and had commented upon the magnitude of the change with the Petter engine as compared with that of the Benz engine. Taking the changes as relative values, the increase in delay with Fuel C over that with Fuel A was approximately 40 per cent. in the case of the Petter engine and 50 per cent. for the Benz engine ; with Fuels D and E, the Petter was still approximately 40 per cent., while the Benz was 250 per cent. It all went to show that the engine influence was distinctly marked, and a factor which could not be ignored.

In connection with the engine influence ; changing the compression ratio by raising or lowering the piston or cylinder virtually changed the engine, particularly in an engine of the Benz type. In any engine the surface-volume ratio would be changed, and in small high-speed engines the change would be relatively great. The better way to change the ratio would be to provide the inlet valve with means for changing the point of closing, so that more or less of the change could be rejected during the early part of the compression stroke.

Squad.-Leader W. Helmore said that he was very much in agreement with Mr. Dicksee about engine results. If one paid regard to the experiments given by Mr. Le Mesurier and took the fuels as representing any reasonable spacing of fuels in order of merit, the state of affairs was not very clear. If the Benz engine were taken, one got the fuels A, C and D with a very small difference of ignition delay. Then one took the Petter engine and got very big differences of delay. Taking the Gardner engine, the fuels were spaced evenly. At 1000 r.p.m. it was very difficult to find any suitable engines for grading these fuels. He thought that, using the apparatus at the Royal Aircraft Establishment, his colleagues and himself were fully in agreement with Mr. Le Mesurier's tests so far as regarded the order of the fuels A, C, D and E, and in that respect he felt that their own attempts had been a success. They had made this apparatus for the purpose of testing this property of fuels, and they admitted quite frankly that they did not claim any basic physical factor when they gave any spontaneous ignition temperature. What they hoped to do was to match fuels to a given standard. If there was any possibility of Mr. Le Mesurier doing any other engine tests, it would be interesting to prepare from a good and a bad fuel a blended fuel to match any fuel that Mr. Le Mesurier would put up to them, and make a number of

engine tests between two fuels which were a match on S.I.T. It would be helpful and encouraging to go on with the work if these engine results proved that the fuels were not easily identifiable from the point of view of spontaneous ignition temperature. He noticed that in the Robey engine there was only a difference as between A and C and D and E of 2° of delay—that is to say, between the best and the worst fuels—and anybody who had worked with a R.A.E. indicator, and appreciated how difficult it was to get within 2° from the point of departure of the explosion line, would appreciate what that meant. For engine testing a method would have to be devised for measuring the low angle. In the ordinary laboratory it would be impossible to grade fuels where one had only 2° to play with. The main thing that was wanted from the point of view of standardization was to find a means of measuring the point at which it could be claimed that there was a pressure rise above the compression pressure. One was practically drawing a tangent to a circle at that point. The result was that whatever engine was developed must give a very wide difference of delay angle between fuels, so that one could call upon the R.A.E. indicator to sort it out, or upon any other indicator capable for the purpose which functioned at high speeds.

Dr. W. J. D. Van Dyck said that with regard to the question raised by Dr. Ormandy on the possibility of a relationship existing between the quality of an oil in respect of gas-making and its quality as a Diesel fuel, the Bataafsche Petroleum Maatschappij's research laboratory at Amsterdam had been experimenting, in co-operation with the Engine Testing Station at Delft, along analogous lines, and in their opinion there is no doubt but that there is a close relationship between the thermal stability of a hydrocarbon and its ignition quality.

In one of the experiments the vapours of hydrocarbons in the absence of oxygen were passed through an electrically-heated Pyrex tube and heated quickly to a temperature of 625° C. for half a second, chilled immediately, and the number of molecules that were broken down and the number that were newly created measured.

As in this short time only a small proportion of the vapours was cracked, the amount cracked was still proportional to the cracking time, so that it was possible to calculate the initial cracking speed, i.e., the number of molecules that decompose or are formed respectively per unit of time at that temperature.

It has now been found that there is a close correlation between the number of bonds broken per second and the cetene number.

Eight different fuels from seven different origins and of most widely differing character, covering the whole range of the Diesel fuels, were examined. As would be seen from Fig. 1, the points showed a close correlation, and it was possible to draw a smooth curve going through all the elliptic areas that represented the measurement error of each point.

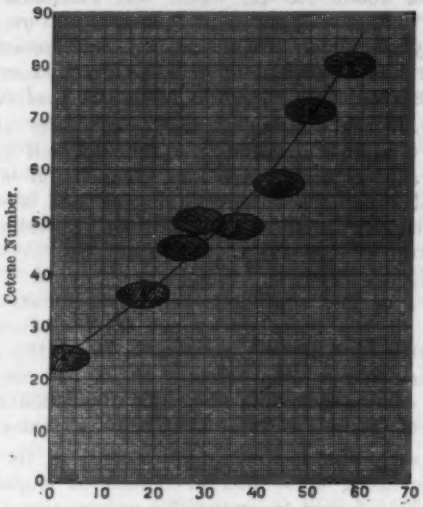


FIG. 1.

Mr. W. A. Tookey (President, I.A.E.) said that he would first look back and consider in retrospect the development of the internal combustion engine in its relation to spontaneous ignition temperatures since 1890. At about that time they were in the early stages of getting away from the original Otto gas engine—the slide valve engine with its 40 lb. compression pressure and probable working compression temperature of about 230° C.—where a small quantity of gas was collected and ignited in a pocket and the flame carefully nursed so as to keep it kindled until it was mechanically moved to connect with a touch-hole into the main cylinder to fire the main charge. Soon afterwards came the externally heated ignition tube, and to secure prompt and rapid ignition it was found necessary to maintain a temperature corresponding to a "cherry red" heat. In those days they could not be more precise than was indicated in that description. That "cherry red" heat, according to the text books, was of the order of 900° C.

In the development of the oil engine of that period, compression pressures were of the order of 40 lb. per sq. in., and it would be remembered that on the light loads many misfires occurred unless a constantly burning lamp was provided for heating up the vaporiser. At higher compression pressures, later types of oil engines were started by preliminary heating with a lamp, to a temperature of about 400° C., which was estimated when the bulb looked "dull red in the dark"—a temperature difficult to appraise in daylight hours. All these were "self-ignition" engines, and were therefore dependent upon what had that evening been defined as the spontaneous ignition temperature of oil fuel.

The Campbell cold-starting engine came along about 1915, and to Hugh Campbell, of Halifax, closely followed by Ruston's, of Lincoln, was due the modern high compression oil engine of the horizontal type. The Campbell engine had a compression volume ratio of from 10 to 10½, equivalent to a working compression temperature of 470–480° C. and about 310° C. with a cold cylinder. Ruston's, however, found that to deal with all the suitable grades of fuel which the petroleum industry sent from time to time, it was necessary to put the compression volume ratio temperature still higher, namely, to 13 or 13½ to 1, which gave a working compression temperature of 530–540° C., and a cold starting compression temperature of about 355° C.—a figure of much interest in view of what had been said that evening.

From this retrospect it would be evident that the mechanical engineer, specialising upon internal-combustion engine problems, had hitherto been forced to arrange for compression temperatures amply sufficient to bring about not only spontaneous ignition, but prompt and efficient combustion within the cylinder walls under diverse operating conditions to be met with in practice in various parts of the world. The promise foreshadowed by the papers presented that evening was most encouraging, and the contribution of our confrères from Holland was unquestionably valuable. The good work done at Farnborough was also of the greatest importance, and at last there seemed to be the basis of a useful and practical standard for appraising relative values of oil fuel for use in compression ignition engines.

It was probable, however, that the determination of the S.I.T. value of liquid fuels would have to be correlated to the characteristics of combustion in engine cylinders for the same oil fuels. It was agreed that delayed combustion was detrimental, not only because of the phenomenon of what was termed "Diesel knock," but because it increased the problems of heat dissipation through cylinder and piston walls and favoured the deposition of carbon.

It must also be remembered that when delayed ignition occurs, the maximum combustion pressure was not attained until the piston had moved some distance from its inmost position. The change of volume that this involved must have an influence upon the chemical processes then proceeding, and, indeed, a part of the efficiency consequent upon the use of high compression volume ratios was to some extent lost. Experience with hot bulb engines had definitely shown that with delayed ignition carbon deposition became a bugbear, and as the compression temperatures had been increased and combustion quickened so carbon troubles had tended to disappear. In two-stroke engines of modern design with high compression, this was particularly to be discerned. Highest thermal efficiencies, smooth running and minimum of operating difficulties were always obtained with well-advanced ignition timed to create maximum pressures within 10 degrees of crank angle after the inner dead centre, and with the methods of determination of spontaneous ignition temperature that had been discussed that evening it would perhaps be possible for the fuel oil specialist to assist the engineer in the work that now lies before him.

The President called upon the meeting to accord a very hearty vote of thanks to the authors of the four papers. This was given with acclamation, and the meeting terminated.

The following written contribution to the discussion was subsequently received :—

From **Mr. A. K. Bruce.** He agreed with Mr. Le Mesurier in his conclusions that the value of data from spontaneous ignition tests is mainly concerned with determining the ease of starting with different fuels.

The question of the ignition delay must be thought of with due definition of the limits fixed by the rotative speed of the engine, since it is a misuse of language to refer to a "long" period of delay in a case where an engine is operating at, say, 1500 r.p.m. For example, in the instance of the Benz high speed engine referred to, the time per revolution is only 0.06 second, and the equivalent time for two degrees ignition lag is only about three ten-thousandths of a second.

If a further example from practice is taken in a large two-stroke cycle engine with speed 160 r.p.m., the time per revolution is 0·375 second, so that for two degrees ignition lag, the equivalent interval is two one-thousandths of a second, or six times longer than in the high speed engine.

From such figures it certainly appears that Mr. Chaloner does not exaggerate the position by assuming that "a few one-thousandths of a second suffice to prepare the fuel for the ignition

and combustion stage." The difficulty is that we have no language in which to express, adequately, the rapidity at which the changes are taking place, and it has doubtless been the opinion of many engineers who have to deal with compression ignition engines, that the parity between the fuel consumption of large slow speed engines and small high speed engines could not be possible unless the functioning of the fuel injection system and the combustion processes were more or less instantaneous.

Referring to Table VII. in Mr. Chaloner's paper, he thought it opportune to mention that according to Dr. Sass in his work on "Kompressorlose Dieselmaschinen," good combustion in A.E.G. engines required that 20 per cent. of the oil globules should be not larger than two ten-thousandths of an inch; 30 per cent. not larger than six ten-thousandths of an inch, and preferably none larger than two one-thousandths of an inch. To arrive at such an atomisation the injection pressure was 4000 lb./sq. in. and the orifice diameter 0·024 in.

On the subject of the spontaneous ignition temperatures of the fuels commonly used in commercial engines, he noticed a rather interesting coincidence between the surface temperature of the combustion chamber parts and the spontaneous ignition temperature. Very accurate tests made by Messrs. Sulzer Brothers on a large two-cycle engine showed that the highest temperature reached, at full load, in the cylinder cover or piston was approximately 300° C. On the walls, the highest temperature reading was 333° C. According to these figures, the spontaneous ignition temperatures of most of the fuels referred to in the symposium are comparatively close to the surface temperature of the combustion chamber parts, at all events, in slow speed two-cycle engines, and the variations in surface temperature have been found to change inversely as the square root of the speed.

Reference to the combustion chamber led to the difference between the conditions in the explosion vessel of the Farnborough apparatus and the conditions in the combustion chamber of an actual engine. On this point no doubt Mr. Foord and those working with him have details of the work done in America, by Professor Schweitzer and others, on oil-spray research. In a recent paper contributed to the Transactions of the American Society of Mechanical Engineers, Professor Schweitzer refers to tests on the penetration of oil sprays, according to which it was found that with 6000 lb./sq. in. injection pressure the spray travelled 28 in. into cold air at a pressure of 200 lb./sq. in., the density of which corresponds to 450 lb./sq. in. in hot air. With 1000 lb./sq. in. injection pressure the penetration was about the same, but in atmospheric air the spray "shot across the laboratory."

It seemed that connection between the character of the oil spray and the spontaneous ignition temperature is too intimate to be neglected in a study of ignition delay, but he realised the difficulty of investigating all these points simultaneously.

From **Mr. J. Kewley** (based on information received from Mr. J. Baddiley): Some of the pitfalls which stand in the way of determining spontaneous ignition temperature are illustrated by the work carried out by Messrs. Coffey and Birchall in 1929. They used an ignition pot, which was heated by the hot air, which was eventually introduced into the bottom of the pot. The pot was 4 in. high and $1\frac{7}{8}$ in. diam. With the use of this apparatus they found that certain gasolines had a spontaneous ignition temperature of 320° C. They then investigated the behaviour at higher temperatures, and found that at 335° C. ignition ceased and that at 420° C. a second spontaneous ignition temperature was observed. In all cases the time lag was about 2 seconds. All tests were made by letting in one drop in not less than 2 minutes. It was found that two drops in repeated succession brought about ignition in the dead zone. Perhaps earlier workers have encountered the same phenomenon without recognising it—*e.g.*, the figures given by Weerman (J.I.P.T., 1927, 13, 244–280), seem to point to the existence of a similar "dead zone." The explanation of this phenomenon is rather obscure. Mr. Birchall thinks that the "spheroidal state" accounts for the two flashpoints. Thus, below 335° the drop "wets" the floor of the pot and evaporates rapidly, but above 335° the drop is cushioned by its own vapour and evaporates slowly. The two flashpoints would thus be those for "rich" and a "lean" mixture respectively. He has no other experimental evidence in support of this view. Messrs. Coffey and Birchall found that the addition of anti-knock dope in small concentrations diminished the dead zone and finally eliminated it altogether, both spontaneous ignition temperatures being raised. They made a further remarkable observation that, if the iron floor of the vessel was replaced by grains of carborundum, no ignition was observed before 508° C.

From **Dr. F. H. Garner**: Mr. Foord is to be congratulated on the development of the apparatus described for the measurement of spontaneous ignition temperatures, and for the ingenious electrical timing arrangement for injection and explosion. The apparatus in the present form is, however, rather complicated and consequently expensive to make, and it would therefore be interesting to know how the results compare with the simpler form of this apparatus previously used, both as regards the relative order of different fuels and the degree of accuracy obtainable. It is to

be hoped that Mr. Foord will at a later date be able to give some data on the relation between the results obtained in this apparatus and actual engine tests, as this feature is naturally the main justification for the determination of spontaneous ignition temperature.

The recent work in America in connection with the adaptation of the C.F.R. engine for Diesel fuel testing would appear to provide a basis for the flexible unit which Mr. Le Mesurier postulates for the testing of Diesel fuels. The present position in so far as the knock rating of gasolines is concerned, where there has been a world-wide adoption of an octane scale, must be attributed largely to the simplification in the procedure of engine testing as a result of the work of the C.F.R. Committee. At the commencement of that work a very large number of types of testing engines and variations in methods of procedure for carrying out knock-rating tests were in vogue, which have now been largely eliminated, with the result that at the present time it is possible to rate fuels accurately, although certain details still have to be worked out. These do not, however, appear to necessitate any fundamental change in the testing unit itself.

The conclusion reached by Mr. Broeze, that discrepancies in the rating of fuels on different types of engines are relatively unimportant and that therefore a standard rating method can be adopted, is of the greatest importance. It would be of interest to have some further data concerning the fuels of extremely high-boiling range (400–500 °C.) which have been found not to be satisfactory on the standard method of rating which he has adopted.

From **Dr. D. Schafer**: Mr. Chaloner mentioned that the spontaneous ignition points of a large number of petroleum gas oils stand on almost the same level. This fact also applies to other inflammable substances. It was the positive basis for the introduction of the method for determining ignition value (*cf.*, Jentzsch, Z.d.V.D.J., 1924, No. 11), according to which not only the spontaneous ignition point, but also the minimum requirement of oxygen for the ignition must be determined if accurate data for the tendency of the substances under investigation to ignite are to be obtained.

Exhaustive experiments have shown that it is justifiable to assign equal importance to the igniting action of the air under definite pressure as to the igniting action of a definite accumulation of oxygen in the unit of space at atmospheric pressure. As a matter of fact, it is not the final condensation pressure as such, but primarily the quantity of oxygen present in the unit of space which is of the decisive importance in the processes in connection with the ignition of motor fuels. In this respect it is immaterial

what kind of motor it is. Most of the objections put forward by Mr. Chaloner against the Jentzsch Tester are based on theoretical considerations, or have originated from an incorrect application of the testing method. At the present time it is not disputed that the spontaneous ignition properties of motor fuels depend upon the following factors: (1) temperature; (2) amount of oxygen in the atmosphere in the unit of space; (3) superficial area of the fuel in relation to the volume enclosed (degree of distribution); (4) chemical constitution of the fuel. The effect of all these influences can be determined in a simple and unmistakable manner by Jentzsch's method.

A point of special importance, moreover (and this has not been mentioned by Mr. Chaloner), is that in the ignition value tester not only fluid motor fuels, but every form of inflammable substance, whether gaseous, liquid or solid, can be tested for their tendency to ignite under similar conditions and by the use of analogous valuation figures. Thus the ignition value can justifiably take its place beside the calorific value, to which it forms a valuable supplement in the case of, *e.g.*, fuel oils. Concepts such as knocking value, benzole value, octane value, capacity value, aniline point, etc., lose their significance when they are not applied to motor fuels. The ignition value, on the other hand, is the universal concept which applies to the tendency of every inflammable substance to ignite. The greater the tendency to ignite, therefore, the higher the ignition value. It would be difficult to give a technically more applicable description which in *one* value embraces the three most important factors of spontaneous ignition: "temperature requirement," "oxygen requirement" and "chemical constitution." One need only then keep constant the fourth factor—the superficial area of the fuel in relation to the volume—in order to be able to compare, by means of incontrovertible valuation figures, the tendency of various substances to ignite spontaneously.

By the introduction of the "distinctive ignition value" (Kennzündwert) mentioned by the lecturer it has been possible to arrange all the substances in a suitable scale according to their tendency to ignite.

From **Mr. H. V. Stead**: It is remarkable how quickly and efficiently this question of the behaviour of fuel oil in Diesel engines and their testing is being investigated under the influence of the phenomenal advances made by the high-speed compression ignition engine. The necessity for such investigation for high-speed work is quite clear, yet in the important marine field, where speeds are slower, design and experiment have always been used to fit the

engine to the oil and not the oil to fit the engine. Of course, the most noticeable result of the latter procedure is the much higher rate of progress in design.

The opinion expressed by Mr. Chaloner on many occasions should be remembered, namely, that the development of the oil engine should be along lines rendering it more flexible as regards the fuel it can use. Is there not something a little inconsistent with this view in the attitude of those petrol engine firms now building C.I. engines and of the oil companies themselves?

The authors wrote in reply as follows:—

Mr. F. A. Foord: The salient feature of the discussion regarding the Royal Aircraft Experimental Establishment Spontaneous Ignition Temperature Apparatus appears to be the universal misconception as to the object of the apparatus and the possibilites claimed for it.

Several speakers have referred in detail to differences between the figures obtained in the apparatus and those which might be obtained under running conditions with the same fuel in a typical engine.

It was made very clear in the paper, and Squadron Leader Helmore, in his remarks during the discussion, again emphasised the point, that the apparatus is not intended to give any absolute values numerically for spontaneous ignition temperatures or to reproduce the results obtained with heavy fuels in the engines themselves.

This is obviously impossible, as engines of varying design must inevitably disagree as to the number of degrees of delay angle actually recorded with any given fuel, owing to the wide differences of design of head combustion chamber, injection mechanism, turbulence, etc.

The R.A.E. spontaneous ignition temperature apparatus has as its sole object the careful matching and grading of various types of fuels. From the results obtained, it is possible to show by means of time-temperature curves the superiority or inferiority of any given fuel when compared with another fuel. Thus by taking any fuel of known performance and characteristics in an engine, results obtained in the apparatus will show whether any other fuel is likely to be better or worse than the fuel referred to, having particular regard to ease of starting and sweetness of running.

It has also been found possible to blend fuels of varying character in such a way that a match can be made with a fuel of a given standard. In other words, the aim of the apparatus is very similar in character to that adopted for matching and grading fuels for

petrol engines as regards anti-knock values. The work described by Mr. Broeze is likely to be very helpful in this connection, particularly as the two reference fuels of which he has such a good experience, namely, cetene and mesitylene, seem to be such reliable standards, as is borne out by the results of his very interesting engine experience. It is proposed to examined these substances in the R.A.E. spontaneous ignition temperature apparatus, with a view to establishing the time-temperature curves for a good and a bad fuel; each curve can then be used as a datum line for the purpose of grading fuels of intermediate quality.

Several speakers have stressed the necessity for co-relation between engine results and those obtained with the R.A.E. apparatus, and it is felt that the work carried out by Mr. Le Mesurier in this direction is an interesting and useful first step.

Squadron-Leader Helmore, in his remarks, has drawn attention to the broad agreement obtained during these engine tests with the results of the same fuels in the R.A.E. apparatus, particularly as regards ease of starting, and on the whole the same may be said of the delay angles when the discrepancies which existed between the various engine results and the difficulties of measuring the actual delay angles are taken into consideration. There is no doubt, of course, as to the necessity for this work of co-relation with engine results, as the whole object of the apparatus is to match fuels with others having known characteristics in an engine. This point is being watched and the R.A.E. have already done a good deal of work in this direction, and this work is being extended considerably.

Dr. Ormandy, in his remarks, stated that it would be exceedingly interesting to have something in the nature of a Ricardo variable compression Diesel engine.

It can be stated that such an engine does in fact exist, namely, the Ricardo E.42 engine, and is being experimented with at the R.A.E., but it has been found that although interesting results may be obtained, the changes caused by varying compression of the engine itself have a major effect on spray penetration and combustion which tends to mask the more important fact of delay angle when various fuels are used.

It is felt that this difficulty must be present with all engines used for standard testing purposes, which are designed to reproduce varying conditions which do occur in other engines of entirely different design.

The R.A.E. apparatus aims at establishing a definite order of merit for fuels that will hold good for any normal compression ignition engine, and it is hoped that this ability to match fuels will

be useful where any particular engine is desired to run on a blend differing from its normal fuel.

Dr. Garner stressed the cost and complication of the apparatus, and suggested that a simpler form might suffice for the purpose in view. This has been tried, but it has been found necessary, in order to differentiate between fuels of closely allied characteristics, to have a timing apparatus which is capable of accurately measuring the delay angle. No doubt if the instrument were put into production the details could be simplified and the cost reduced, but the opinion is expressed that in view of the importance of accuracy in such an apparatus, any small extra cost which would result in increased accuracy would be fully justified, having regard to the small numbers of such an instrument likely to be required.

It is realised that a number of points which may possibly effect spontaneous ignition temperatures have yet to be determined; for example, variable distillation curves and effects of pressure, although in this latter case it is considered that the evidence all goes to show that this is a constant factor and can afford to be ignored in order to keep the apparatus as simple as possible. These matters are all under investigation with a view to determining their relative importance, but it is felt, and the experience already obtained goes to show, that the matching and grading of fuels with those of known characteristics is a practical possibility and that such fuels when so matched, when compared in a typical compression engine, would be unidentifiable.

Mr. J. L. Chaloner: As was to be expected, Dr. Ormandy raises a number of very important points, and he would subscribe to his contention, also supported by other speakers, that the fuel burnt in the vapour formed.

The fact that Dr. Ormandy has obtained accurate and consistent results with a very simple form of instrument, and that he is not in favour of an oxygen supply, warrants the Standardization Committee of the Institution giving further consideration to such a suggested form of standardization. Although in certain quarters there have been doubts as to the merits of an ignition temperature measurement for ascertaining the relative suitability of various Diesel fuels, the discussion brought forth much information which certainly points to the desirability of continuing the work of standardization. However, before taking any definite line as regards the form the proposed standard instrument is to take, it is urged that the great amount of information made available during the discussion should be assimilated and carefully considered, and, where possible, amplified by the work carried out elsewhere, as for instance, in the United States.

There is one more aspect which merits reflection at this stage, and that is the difference in the ignition temperature of a petroleum base Diesel fuel and a coal tar derivative. One rather feels that further knowledge on ignition temperatures will eventually help to elucidate the combustion problems associated with the burning of coal tar Diesel fuels.

It should be pointed out in reply to Mr. Dicksee's query that the author's contribution relates purely to the German investigations. It was considered improper to introduce any personal comments. Mr. Dicksee's denial of the contention that every grade of light Diesel fuel oil could be burnt satisfactorily in any type of oil engine is evidently based on an incorrect conception of what constitutes a light Diesel fuel oil. Again, the opinion expressed on that point really refers to combustion only and not combustion in a certain engine running at a particular speed and with a particular b.m.e.p.

With regard to Mr. A. K. Bruce's reference to Dr. Saas' oil globule dimensions, it would appear that Schlaepfer's suggested vaporisation periods for different globule diameters do not agree with Dr. Saas' experiments.

Mr. L. J. Le Mesurier: It is interesting to observe that Dr. Ormandy and Dr. Schäfer hold very different views on the suitability of oxygen in a spontaneous ignition meter. Whereas Dr. Schäfer regards the quantity of oxygen present as being of decisive importance and the pressure effect as negligible, Dr. Ormandy gives instances which appear completely to disprove this contention. Regarding the Moore type of meter, the figures quoted for S.I.T. obtained in the Moore apparatus appear to me to be practically useless. Fig. 1, to which Dr. Ormandy refers, is, however, based on the Farnborough apparatus and is obviously of much more value. It will be seen that, on the whole, the Farnborough apparatus grades the selected fuels on which the tests were made, generally in the same order as the engine, both in regard to starting and running conditions. It appears, however, that there are cases in which the data obtained from the Farnborough apparatus do not completely give the required information as to running conditions in the engine.

Mr. Dicksee's remarks on the influence of the engine design and running conditions are fully appreciated. It is, indeed, extremely difficult to estimate the effect of turbulence and heat transference in the different parts of a combustion-chamber in such a way that the actual temperature of the air in the region of the oil spray can be obtained; but, leaving out the effects of differences in fuel qualities, in studying the problem it is helpful to assume that the only essential factors influencing delay are the temperature and pressure of the air zone in way of the fuel spray.

Both Dr. Ormandy and Mr. Dicksee appear to regard the distillation curve of the fuel as having an important influence, but from consideration of the actual time available for the heating of the fuel droplet, it would appear that the quantity of fuel vaporised must be of an infinitesimal order and that its effect must be relatively negligible.

With regard to Squadron-Leader Helmore's remarks, it is agreed that the results obtained with the Farnborough apparatus are exceedingly promising and reflect great credit on those concerned with the development of this apparatus. It seems, however, too soon to say whether the apparatus will give all the information required in connection with the self-ignition properties of Diesel fuels. It is also true that some of the engine tests fall short of what is required, and it is agreed that the margin of error in the Robey engine tests is much too great. The results carried out in these several types of engine, however, suggest the possibility of developing a suitable type of engine and a technique for conducting the tests which will give accurate information of the type required.

Mr. Bruce points out the importance of defining the "delay period" more precisely. It may be expressed either in absolute time units, such as microseconds, or in terms of crank angle, provided the speed of the engine is stated. The "delay period" of a given fuel measured in absolute time units will be the same in a slow or high speed engine subject to the same conditions of temperature and pressure existing in each engine at the moment of fuel injection. The low speed engine will thus show a shorter lag in terms of crank angle degrees than the high speed engine, and the exact lag may be extremely difficult to determine, particularly in an air injection engine.

The brief summary of the stages in the development of the compression ignition engine, given by Mr. Tookey, indicates progress towards increased compression pressure, thereby reducing "delay period" and widening the range of suitable engine fuels. It is, in fact, due chiefly to the much higher speeds of modern engines that delay period becomes so important and that means for testing the ignition properties of fuels must be devised.

Progress in Hydrogenation of Petroleum during 1930 and 1931.

By E. J. Gohr and R. P. Russell.

The years 1930 and 1931 have shown considerable advance in the hydrogenation art, both in its commercial application and in its technology. Although the process is applicable to coal, oil, and other solid or liquid carbonaceous materials, this paper will be devoted only to those phases which pertain to petroleum.

Large Scale Plant Developments.

During this period of time two large scale commercial plants have been placed in successful operation in the United States. The first of these is shown in panoramic view in Fig. 1, and is located at the Bayway, N.J., refinery of the Standard Oil Company of New Jersey. This plant has an operating throughput of 4000 to 6000 barrels per day, and was initially started on August 7, 1930. The second commercial plant shown in Figs. 2 and 3 is of similar capacity, and is in operation at the Baton Rouge, La., refinery of the Standard Oil Company of Louisiana. This unit was placed in service on May 23, 1931.

In the operation of these plants the oil and previously compressed hydrogen are mixed together and delivered through heat exchangers to a coil furnace, and thence to a reaction chamber filled with a sulphur-resistant catalyst. Ordinarily a pressure of about 3000 pounds per square inch is maintained at this point, together with the desired temperature. The degree of hydrogenation is carefully controlled, depending on the results desired, control in general being maintained by alteration of the operating conditions.

From the reaction chamber the mixed final products and gases pass through heat exchangers and coolers to a high pressure separator, where the liquid product is separated from the unconsumed hydrogen and other gases. The liquid product is finally reduced to atmospheric pressure and sent to rundown pans. The gas from the separator flows to a booster compressor, where it is recompressed to full operating pressure prior to mixing with the feed oil and fresh hydrogen at the exchanger inlet. Gases which are formed in the process are, in many cases, removed to a sufficient extent by solubility in the final liquid product. In other instances it is necessary to scrub the gas with oil under pressure before recompression.

Hydrogen for the process may be produced by any suitable method; but, in general, in refineries where large amounts of refinery or natural gas are available, it can be made readily from these hydrocarbon gases and steam according to the reactions:—

$$CH_4 + H_2O = CO + 3H_2$$
$$CO + H_2O = CO_2 + H_2.$$

After scrubbing out the carbon dioxide, the hydrogen is of sufficient purity for the hydrogenation reaction.

Since no coke is formed in the hydrogenation process, and since the catalysts employed are extremely rugged, the process is virtually continuous. At this writing a run on the large scale plant at Bayway has been in continuous operation for one year. Similarly, at the Baton Rouge Plant a run has been in progress for seven months. In addition to demonstrating the durability of the catalyst, these, as well as other long commercial runs, have shown the operability of the process.

Since their construction, the large scale plants have found service in meeting variations in refinery demand, and as such have produced paraffinic motor lubricants, high A.P.I. gravity burning oils, gasoline and high quality neutral oils. For this purpose, distillates from Colombian, West Texas, East Texas, Mid-Continent and other crude sources have been charged to the plants. All these products have been finished by the usual large scale refinery methods, and were marked by the fact that but little chemical treatment was necessary. This is characteristic of hydrogenated products, because of their low sulphur, good colour and stability. Inspections of some of these products will be given in following sections, wherein the various adaptations of the hydrogenation process will be taken up in more detail.

Technological Developments.

In addition to the above, the past two years have witnessed the development of new methods of catalyst manufacture, whereby it has been possible to obtain greater throughput as well as greater yields and longer catalyst life.

Intensive effort has been directed toward interpretation of the results obtained by hydrogenation of various fractions from a variety of crude sources. Upwards of 150 stocks have been studied under various conditions of catalyst, temperature, time of contact, hydrogen pressure, etc. As a result of this work, it has become possible to predict the type of feed stocks necessary for maximum yield of a given quality product as well as to determine the required operating conditions. Furthermore, information has been obtained which permits operation under conditions for maximum catalyst life and activity.

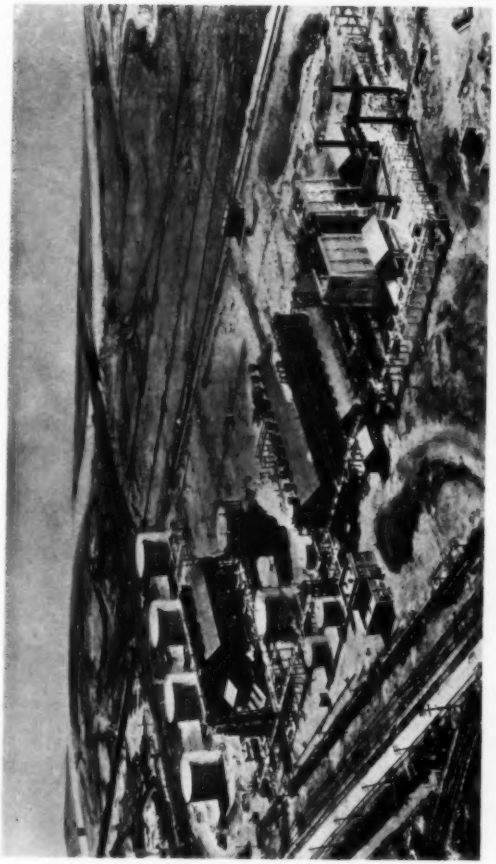


FIG. 1.

PANORAMA OF PETROLEUM HYDROGENATION PLANT, BAYWAY, N.J., REFINERY OF THE STANDARD OIL COMPANY OF NEW JERSEY.

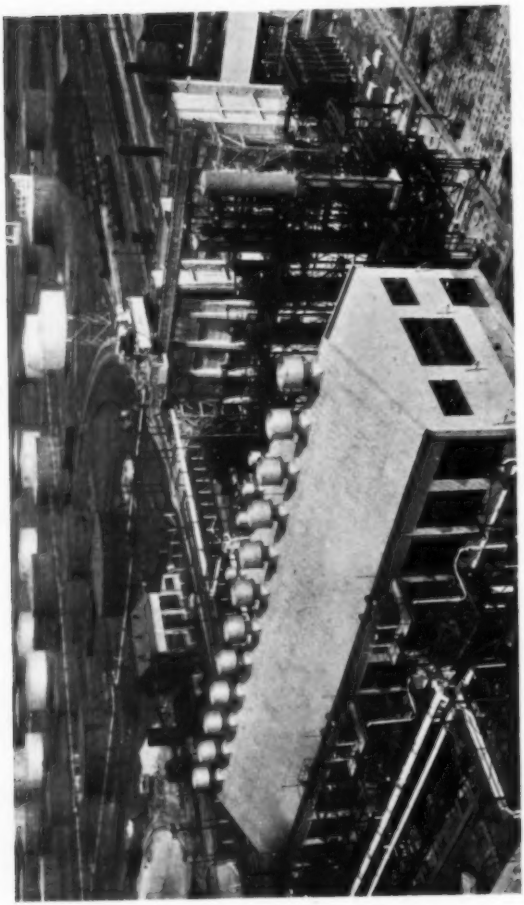


FIG. 2.

PLANT FOR HYDROGENATION OF PETROLEUM AT BATON ROUGE, LA., REFINERY OF STANDARD OIL COMPANY OF LOUISIANA.

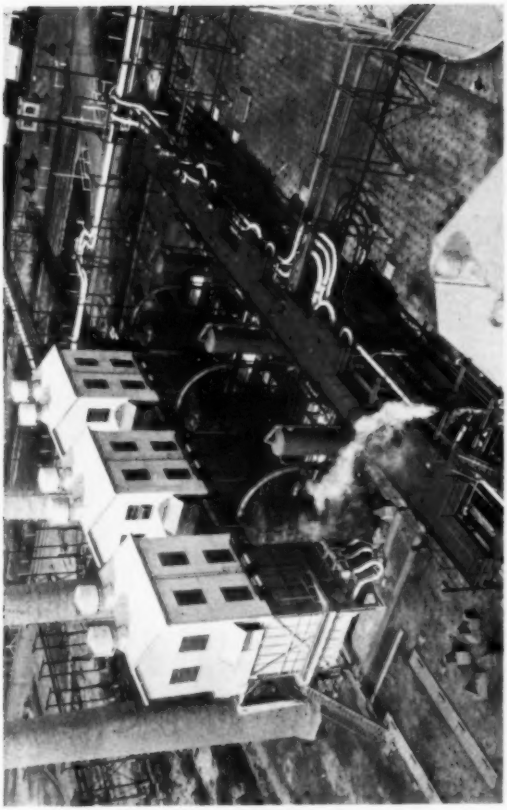


FIG. 3.

HYDROGEN PRODUCING EQUIPMENT AT BATON ROUGE, LA., HYDROGENATION PLANT.

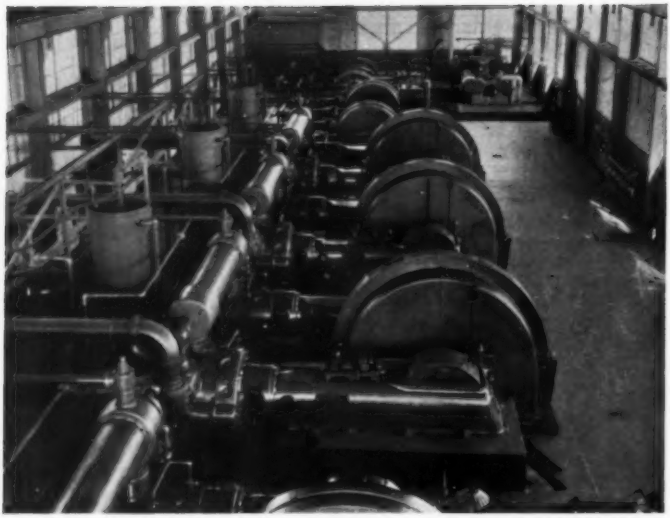


FIG. 4.

INTERIOR OF COMPRESSOR HOUSE, BAYWAY, N.J., HYDROGENATION PLANT.

These studies have shown that, according to the conditions of the hydrogenation treatment and the nature of the catalysts employed, the chemical reactions that occur alter their direction and extent. Three characteristic reactions remain unaltered in direction, however, changing only in extent. The first of these reactions is a species of *purification*, called by Ellis* "hydrocarbonization," and is defined as the tendency to eliminate from the liquid product everything save hydrocarbons. In other words, the alien elements, nitrogen, oxygen and sulphur, present in natural hydrocarbons and bitumens, are preferentially attacked by the hydrogen and removed from the reaction zone as the corresponding gaseous hydrides. The second characteristic reaction is that of *stabilisation*. The hydrocarbons that emerge from the hydrogenation process are by the very nature of the process chemically stable. The third characteristic reaction is that of *homogenising*, by which is meant the tendency to produce a mixture of a more homogeneous nature than the raw material by preferential reformation of the more complex molecules present. A hydrogenated oil is, in general, characterised by relative freedom from complex structures of the asphaltic and resinous types, and relative freedom from the more heavy and complex of the viscous fractions.

Although these three characteristic properties of hydrogenated oils are highly desirable and offer promise of a generally higher level of quality for petroleum products, they are secondary rather than primary in character. The most important properties are those resulting from the chemical structure of the prevailing type of hydrocarbon present in the mixture. For example, paraffinic types are advantageous for lubricants and burning oils, while naphthenic and aromatic forms are preferred for gasoline. However, in commercial production difficulties are encountered which enforce compromise, since crudes that yield paraffinic lubricants and burning oils seldom, if ever, yield anti-knock gasoline. Furthermore, natural paraffinic lubricants give greater and more objectionable carbon deposits than do naphthenic lubricants, but show less consumption and much less change of viscosity with temperature. Similarly, in producing the anti-knock naphthenic or aromatic gasolines, a resulting product of lower purity and stability than the paraffinic fuels is obtained.

In the solution of these difficulties the hydrogenation process offers particular possibilities, since: (*a*) It affords a means of reforming the molecular structure of petroleum hydrocarbons along directed lines, thereby obtaining products of the paraffinic or naphthenic type substantially regardless of crude source; (*b*) the

* Ellis C., "Hydrogenation of Organic Substances" (1930), p. 572.

hydrogenated products, because of their characteristic purity, stability and homogeneous nature, are to a large extent free from the objectionable properties inherent to natural paraffinic or naphthenic petroleum products; (*c*) the flexibility of the process permits use of the same plant with practically the same arrangement of equipment for carrying out all the variations of the process described in this paper.

As a more specific statement of the above, it may be said that the hydrogenation process possesses six adaptations which appear to be of most immediate importance in petroleum refining :—

1. Conversion of heavy, high sulphur, asphaltic crude oils and refinery residues into gasoline and distillates low in sulphur and free from asphalt, without concurrent formation of coke.

2. The alteration of low grade lubricating distillates, to obtain high yields of lubricating oils of premium quality as to temperature-viscosity relationship, Conradson carbon, flash and gravity.

3. The conversion of off-colour, inferior burning oil distillates or light gas oils into high A.P.I. gravity, low sulphur, water-white burning oils of superior burning characteristics.

4. The conversion of paraffinic or aromatic gas oils into low sulphur, gum and colour stable high anti-knock gasolines without production of coke or tar.

5. The desulphurisation and colour and gum stabilisation of high-sulphur, badly gumming cracked naphthas.

6. Manufacture of new and specialised products, such as high flash safety aviation fuel and high solvent power naphthas for use as lacquer diluents and the like. The salient features of these adaptations of hydrogenation, together with examples, are discussed briefly in the following sections :—

Conversion of refinery residues into gasoline and gas oil.—Residues from crude stills or cracking coils may be hydrogenated in the liquid phase to produce in excess of 100 per cent. yield of product consisting of gas oil and gasoline, the percentages of gasoline ranging from 10 to 40 per cent., depending on conditions, the balance being a distillate product. During hydrogenation, the asphalt is completely converted and 60 to 90 per cent. of the sulphur eliminated as hydrogen sulphide. Even if the product charged is highly asphaltic and of high sulphur-content, the gasoline produced is easily finished to a low sulphur, gum stable product.

The gas oil which is obtained may be hydrogenated in the vapour phase and converted completely to gasoline, or, if desired, it may be cracked to produce a gasoline which finishes easily to specification. If the tar produced in the cracking step were returned to the hydrogenation operation and none burned for fuel, the yield of gasoline would be approximately 100 per cent.

The workability of the liquid phase hydrogenation operation has been demonstrated on fuel oil residues from Crane Upton, Panuco, Venezuela, Panhandle, Mid-Continent, Talang Akar, Long Beach, Smackover and other crudes, as well as upon cracking plant tars.

Improvement of low quality lubricating distillates.—Hydrogenation of low quality lubricating distillates in general results in the production of paraffinic lubricants of high viscosity index, high flash points and low Conradson carbon. From 100 barrels of lubricating distillate 103 to 107 barrels of hydrogenated product are obtained, which in turn contain: (*a*) 60 to 85 barrels of lubricating oil of somewhat lower viscosity than that of feed, but of much higher quality; (*b*) 10 to 30 barrels of gas oil; and (*c*) 5 to 10 barrels of gasoline. From 80 to 90 per cent. of the sulphur in the feed stock is eliminated during hydrogenation. Colour is greatly improved, hydrogenated lubricating oils normally showing colours between 10 and 18 Robinson.

During the past two years lubricating distillates from a great number of crude sources have been investigated. Among these have been cuts from Colombian, East Texas, Mid-Continent, West Texas, Californian, Coastal, Venezuela, Van Zandt, Reagan, Burbank, Pecos, Winkler, Santa Fé Springs, and many other crudes.

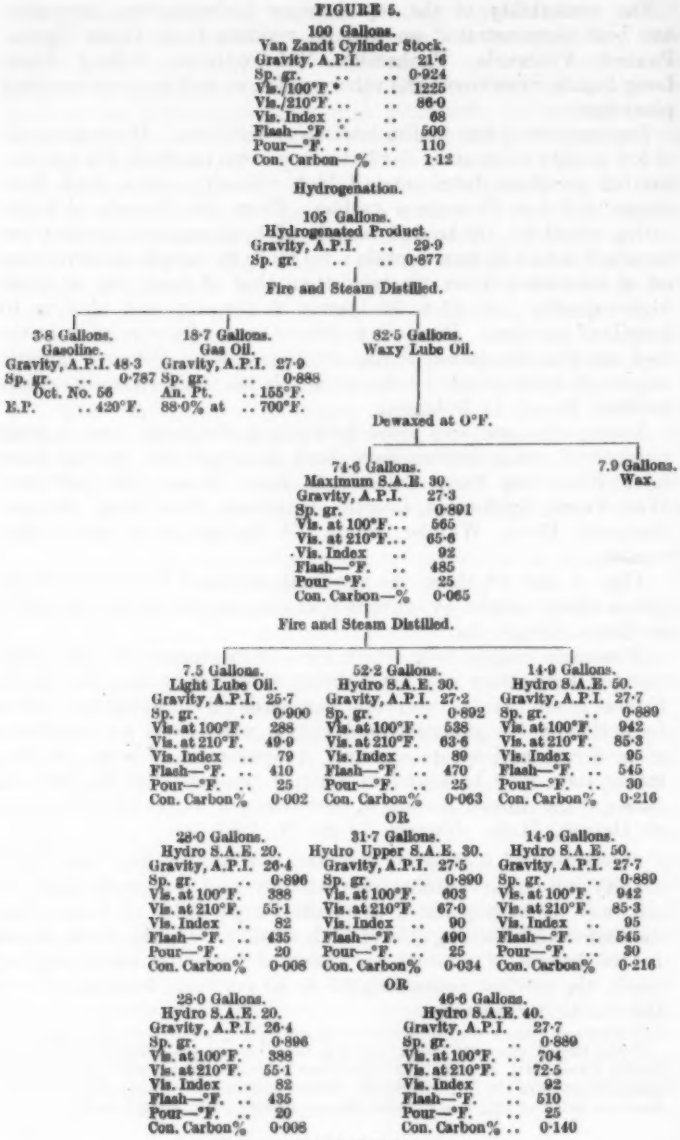
Figs. 5 and 6* show the products obtained from two of the above charge stocks by current operation on the large scale plant at Baton Rouge, La.

Numerous engine tests which have been carried out on hydrogenated lubricating oils have shown them to be superior to the highest grade natural lubricants as regards oil consumption, carbon formation, valve gumming and engine wear, both for conditions of moderate and severe service. A description of some of these motor tests may be found in a paper presented by Haslam and Bauer at the Annual Meeting of the Society of Automotive Engineers at Detroit, Mich., January 19 to 23, 1931.

Production of high grade kerosines.—High sulphur, low A.P.I. gravity, off-colour burning oil distillates and low grade light gas oils may be hydrogenated to produce high yields of water-white distillates and burning oils of high quality. Liquid yields of 100 to 105 barrels of product are obtained from 100 barrels of feed stock, the product containing 65 to 85 per cent. burning oil with the remainder gasoline.

* The term "viscosity index" used in these charts was devised by Dean and Davis, *Chem. Met. Eng.* **36**, 618 (1929) and indicates the viscosity-temperature characteristics of the lubricating oil. Thus paraffinic oils such as Pennsylvania have an index of 100, and Coastal oils a viscosity index from 0 to 20.

FIGURE 5.



* All viscosities are Saybolt Universal.

In general these kerosines meet specifications as to sulphur, colour and smoke tendency, with no other treatment than reduction to flash and viscosity. In some instances, a slight doctor treatment is necessary. Furthermore, the gasoline obtained overhead during reduction of the total hydrogenated product possesses an octane number equal to that from cracked Mid-Continent gas oil, and is practically sulphur and gum free. Its low sulphur-content

FIGURE 6.

* All viscosities are Saybolt Universal.

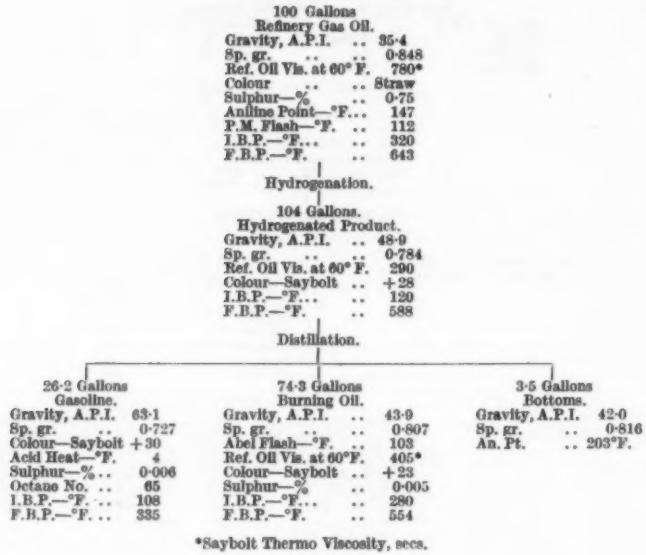
and high resistance to gum formation in storage makes it valuable as a blending agent for naphthas having sulphur-contents difficult to treat to below specification limits.

Stocks which have been treated include virgin and cracked distillates from Mid-Continent, West Texas, Colombia, Alematos, Long Beach, Smackover, Venezuela and other crudes. Fig. 7 shows inspections of the feed and products as produced during current operation on the large scale plant at Bayway, N.J. As indicated in the figure, the inspections of the burning oil and gasoline were made following fire and steam distillation, with no chemical treatment.

Production of stable anti-knock gasolines.—The production of anti-knock gasolines by hydrogenation, although carried out in the same equipment as in those modifications of the process described above, differs from them in that the extent of the hydrogenation is adjusted so that stable, but non-paraffinic, products are formed. In this type of operation the yield of gasoline is

FIGURE 7.

PRODUCTION OF BURNING OIL.



*Saybolt Thermo Viscosity, secs.

usually above 85 per cent. The remaining portion of the charge is converted to gas, since no coke or tar is formed in the process. Any material not converted to gasoline in the first pass through the system is recycled.

The feed stocks which have been used in this adaptation of hydrogenation have included straight run and cracked cycle gas oil from Mid-Continent, California, West Texas, Coastal, East Texas and Talang Akar, as well as materials such as Edeleanu extract. It has been found that gasolines of higher anti-knock quality are obtained from more aromatic feed stocks; in other words, with less paraffinic charging stocks it is possible to obtain higher yields of gasoline of a given knock rating, or much better

knock ratings for a given yield. Table I. shows this relationship quite strikingly :—

TABLE I.

Influence of Feed Stock on Anti-knock Quality.

General Character of Feed Stock.	Highly Paraffinic.	Paraffinic.	Intermediate.	Aromatic.	Edeleanu Extract.
Aniline Point of Feed Stock ..	161° F.	139° F.	102° F.	79° F.	10° F.
Gasoline Yield ..	89·9	91·4	88·0	89·0	85·0
Octane Number of Gasoline, 212° F. engine jacket ..	72	75	85	92	above 100

The gasolines produced thus far have been practically sulphur free, pass doctor and corrosion after lye washing, and are quite gum stable; in a few cases some treating has been necessary, but this has been small in amount. In general, they are quite sensitive to the addition of tetraethyl lead. Table II. shows typical results obtained by the hydrogenation of two gas oils :—

TABLE II.

Production of Anti-Knock Gasoline from Gas Oils.

	Mid-Continent Gas Oil.	California Cracked Gas Oil.
FEED STOCK—		
A.P.I. Gravity	37·8	25·7
Sp. Gr.	0·836	0·900
I.B.P. °F.	435	342
% at 460° F.	3·5	31·0
% at 550	90·0	91·0
F.B.P., °F.	629	602
% Sulphur	0·179	0·554
Aniline Point, °F.	159	79
HYDROGENATED PRODUCT*—		
Yield, % by vol.	86·5	89·0
A.P.I. Gravity	56·4	43·7
Sp. Gr.	0·753	0·808
I.B.P., °F.	86	105
% at 212°F.	36·0	19·0
% at 284	61·0	47·5
% at 356	83·0	85·5
% at 374	87·5	90·0
F.B.P., °F.	433	417
Octane Number	75·1	94
Dissolved gum, mg.	3·6	2·8
% Sulphur	0·022	0·017

*As received from hydrogenation unit.

The value of these highly anti-knock gasolines as blending agents is readily apparent. In this connection Haslam and Bauer (*loc. cit.*) have shown that high Octane Number hydrogenated fuels are equal, if not superior, to benzole for this purpose.

Finishing of naphthas.—By mild hydrogenation a high sulphur, high gum, and unstable gasoline may be rendered stable with about 50 per cent. of the sulphur eliminated under such conditions of operation that the anti-knock value is held substantially constant or lowered to about the same extent as would result from a light chemical treatment. No appreciable change is made in the boiling range of the naphtha. This type of treatment is known as hydrofining and is illustrated in Table III.:—

TABLE III.

Hydrofining Cracked Distillate.

	Charge Cracked Distillate.	Hydrogenated Product (93% Yield).
A.P.I. Gravity	54·9	56·3
Sp. gr.	0·759	0·753
% Sulphur	0·097	0·055
Colour, Saybolt	Yellow	+23
Octane Number	81·6	82·2
Preformed Gum, mg.	77·3	3·8
Copper Dish Gum, mg.	—	1·5
I.B.P., °F.	88	112
% at 140° F.	—	5·0
% at 158° F.	—	12·0
% at 212° F.	35·0	38·5
% at 284° F.	—	69·0
% at 302° F.	60·0	—
% at 356° F.	—	92·0
% at 374° F.	82·0	95·5
F.B.P., °F.	432	390

On the other hand, when desired, hydrogenation may be so operated as to eliminate not only almost all the sulphur from a high sulphur cracked or natural naphtha, but also to produce a marked improvement in anti-knock quality and at the same time increase very largely the lower boiling fractions.

Manufacture of new products.—It has been found that hydrogenated fuels possess one characteristic among others which is quite different from that of straight run or cracked naphthas in that the heavier fractions have the best anti-knock qualities. This is shown graphically in Fig. 8*, where octane numbers are plotted against various distillation points for virgin, cracked and hydrogenated fuels. The Otto-cycle air-cooled aviation engine

* From Haslam and Bauer (*loc. cit.*).

has the advantage of very light weight per horse-power delivered, with the disadvantage of using very volatile fuel of very low flash point. The Diesel-cycle engine, on the other hand, has greater weight per horse-power but a safety advantage in that a high flash-point fuel is employed. For positive fuel injection and atomisation an Otto-cycle engine cannot advantageously use present non-volatile fuels because of their severe detonating characteristics. However, because of the property of high anti-knock quality in the high-boiling motor fuel fractions, hydrogenation yields a high

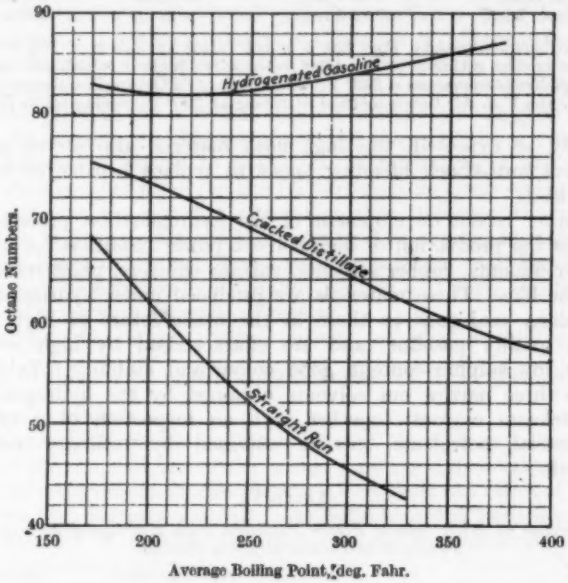


FIG. 8.

ANTI-KNOCK CHARACTERISTICS OF HYDROGENATED GASOLINE, STRAIGHT-RUN GASOLINE AND CRACKED DISTILLATE PLOTTED AS A FUNCTION OF BOILING RANGE.

flash safety fuel of extremely good quality, making possible developments of this nature, particularly in airplane and marine fields. Table IV. shows a comparison of specifications of commercial gasoline and kerosine, with those of hydrogenated high flash safety fuel now being produced commercially.

TABLE IV.

Comparisons of Specifications of Commercial Gasoline, Kerosine, and Hydrogenated Safety Fuel.

	Average Commercial Gasoline.	Kerosine.	Hydrogenated Safety Fuel.
A.P.I. Gravity	59.0 –68.0	46.0	28·5
Sp. gr.	0·71–0·74	0·797	0·884
Initial °F.	90 to 105	380	309
End Point °F. ..	390 to 435	550	411
Flash °F.	–40 to –55	107	107
Octane Number ..	65 to 75 at 212°F.	Below 50 at 212°F.	93 at 300° F.*
Gum (Cu. Dish) ..	5 to 7 mg.	No data.	4·8 mg.
„ (Porc. Dish) ..	2 to 4 mg.	„	2·0 mg.

* Hydrogenated Safety Fuel has a knock rating in excess of 100 Octane Number on the rating scale used for automotive fuels in which the testing engine jacket temperature is 212° F. The figure of 93 Octane Number as given is under the U.S. Air Corps method of rating at 300° F. cooling temperature.

As may be expected, this high flash material also serves as an excellent anti-knock blending agent to replace benzole or tetra-ethyl lead.

Another recent development of the hydrogenation process has been in the production of high solvent power naphthas for use as lacquer diluents, rubber solvents, varnish thinners, paint removers and the like. These materials are produced under hydrogenating conditions analogous to those in the manufacture of high anti-knock quality gasoline, and are characterised by high solvent power, low sulphur-content, good colour and stability. Table V. shows three narrow cut solvents obtained by the hydrogenation of Edeleanu extract, together with an inspection of a typical commercial petroleum solvent obtained by ordinary refining methods :—

TABLE V.

Comparison of High Solvent Power Naphthas from Hydrogenation with those Produced by Present Refining Methods.

	Hydrogenated Solvents.			Commercial Solvent.
A.P.I. Gravity	34·7	28·7	25·6	45·0
Sp. gr.	0·851	0·883	0·901	0·802
Colour, Saybolt	+25	+27	+27	+25
Aniline Point, °F.	—22*	—50*	—27*	140
% Sulphur	0·02	0·03	0·02	0·10
I.B.P., °F.	286	318	340	320
F.B.P., °F.	374	398	418	410
Kauri-Butanol Value†	73	78	80	32

* Extrapolated values.

† A standard method in the paint and varnish industry, denoting the amount of solvent naphtha which can be added to a standard gum solution with coagulation.

Flow in Pipes in the Critical Region.*

By E. S. L. Beale and P. Docksey, B.A.

Introduction.

The literature of flow in pipes contains no reports of an extended investigation into the flow in particularly rough pipes. A considerable number of figures are available, but they have mostly been obtained on commercial pipes under conditions which prevented the use of a large range of experimental conditions, and the results available are for flow under a high degree of turbulence. If reference is made to the graph of "Stanton Curves" in the paper on fluid flow by the authors[1] it will be observed that no attempt was made to extrapolate the reported values for the rougher pipes in the direction of lower velocity for the good reason that insufficient was known about the shape of the curves near the stream-line region to make the extrapolation of any value. For the smoother pipes the line for turbulent flow was extrapolated so as to cut the line for stream-line flow following the method used by Walker, Lewis and McAdams, and others, but it can readily be seen that this method gives a result over 50 per cent. higher than the points determined by Reynolds, Stanton and Saph, and Schoder in certain parts of the critical region.

Further, the lower critical velocity on this method appears to be at about $\frac{vD\rho}{\eta} = 800$ to 1000 instead of over 2000 according to Stanton's work.

It was therefore decided to carry out a set of experiments to decide the shape of the curves in this region and its neighbourhood, and later decided to extend the work to include the effect of joints, elbows, and entrance and exit. It should be noted that in practice the transfer of viscous oils through pipes frequently falls in or near the critical region.

Previous investigators into the flow in the critical region have reported that the conditions of flow are very unsteady and that results were unreliable in consequence. The method used has been in practically all cases to keep the flow constant, and to read the pressure on manometers inserted at suitable gauge-points in the line so as to allow a good "calming" section at the entrance of the pipe. If it is desired not to introduce the uncertainty of applying entrance and exit corrections to the observed pressure drop such an arrangement as this is inevitable.

* Paper received June 30, 1932.

[1] *J.I.P.T.*, 1928, **14**, 236–262.

This is no doubt the best method of pressure measurement during the steady flow of the stream line and the fully turbulent region, but is quite unsuited to work in the critical region. In the practical case of transmitting a fluid along a pipe this difficulty is usually not met with, since the pressure drop is kept constant and the rate of flow is most frequently measured from the quantity delivered over a period of time. Moreover, no special care is taken about entrance conditions.

It was decided to imitate these conditions as closely as possible in experiments, using square-mouthed entrances and exits from the experimental pipes into large tanks and applying a correction for them. The pressure being maintained constant, the flow was measured over a period of time and by this means a good average was obtained. In this way the results obtained in the critical region showed as good consistency as those in the stream line and turbulent regions.

Stanton's experiments have shown that when results are reduced to show the relation between $R/\rho v^2$ and $\frac{vD\rho^2}{\eta}$ the results obtained are of universal application, not only both to liquids and gases of any viscosity and density, but also to pipes of different diameters so long as the conditions at the surface are dynamically similar. Although the present experiments have been confined to small diameter pipes and water they may be used with confidence in the case of larger diameters and fluids of other viscosity and density. It is assumed that the reader is familiar with this method of interpreting results. It is fully described in the "Dictionary of Applied Physics" and in the paper by the authors to which reference has already been made.

It is a noticeable feature of the most reliable results in the critical region that the Stanton curves have an S-shaped bend in them. It has been customary to assume that in practice where disturbances to flow in the way of entrance, joints and fittings are present, this S bend would probably not be obtained, and to use the extrapolated curve for turbulent flow in the critical region, thus giving a factor of safety. The experiments described in this paper show that even with the roughest jointed pipes the S-shaped bend is obtained.

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[2] R = Frictional force per unit area of wetted pipe surface.
v = Velocity.
D = Pipe diameter.
η = Viscosity of fluid.
ρ = Density of fluid.

Apparatus and Experimental Method.

The fluid used in these experiments was water, and the variation in $\frac{vD\rho}{\eta}$ was obtained by increasing the pressure drop and temperature. The apparatus was arranged in two ways, firstly for low pressure drops (1·5 to 110 cm. of water) and secondly for pressure drops for 60 cm. to 10,000 cm. of water.

In the first form the inlet end of the experimental pipe was connected to a one-gallon tank provided wtih an overflow weir to give a constant level. The outlet end projected into a similar receiver of smaller diameter. The inlet tank was rigidly fixed in position, while the outlet tank could be raised or lowered to give the desired pressure drop down the pipe.

To make the manipulation of the pipe easier, a 9-inch length of 1½-inch diameter rubber hose was introduced between the inlet end of the pipe and the constant level tank. Calculation shows that the friction in this section is entirely negligible, its only effect being on the ratio of diameter at the entrance, which is dealt with later.

A pump was arranged to deliver an excess of water to the inlet tank, the amount of which was adjusted to be the same for all conditions of flow, since this was necessary if the water level in the inlet tank was to be maintained truly constant throughout the experiments.

The pressure drop was measured on a scale divided in millimeters, fixed at the outlet end. A zero was first obtained by raising the outlet tank until the flow ceased and the level was the same as that in the inlet tank. The correct excess of water was supplied to the inlet tank at the same time. This allowed a zero mark to be obtained on the scale by means of a dipping rod with a pointed end which was brought down to the surface of the water, the scale being rigidly clamped in position throughout the operations. The outlet tank was then lowered the desired amount and dipped again. The total error in measuring the pressure was estimated as 0·2 mm. of water, so that for pressure drops of 2 cm. of water or greater the error was less than 1 per cent.

Tests with this apparatus were carried out at room temperature, the water temperature being read by thermometer at the outlet tank.

The flow in this and in the second form of apparatus was measured by collecting the outflowing water over a fixed period of time and either measuring the volume or weighing, depending on the quantity collected. Three repeats at least were made for each flow. The error in making this measurement was estimated

at 2 per cent. for the highest flows and considerably less than 1 per cent. as the flow decreased.

When the measurement of the pressure drop was subject to its largest error, the flow could be read most accurately, and vice versa; the error involved in the measurements with this apparatus thoughout most of its range should therefore be less than $\pm 1{\cdot}5$ per cent., with the highest accuracy in the middle of the experimental range.

The values of $\frac{vD\rho}{\eta}$ covered by experiments with the low-pressure apparatus ranged from 200 to 6000, so that they included the critical region. For the higher pressures the inlet end of the pipe was screwed into a tee ($1\frac{1}{4}$-inch internal diameter), to which connection was made to the pump and also to two manometers. For pressures up to 300 cm. of water a water manometer was used, and for pressures from 300 to 2000 cm. of water a mercury manometer, the zero of which was checked against the water manometer at its highest pressure. Only a few tests were done at higher pressures than 2000 cm. of water, and for these a carefully calibrated bourdon tube gauge was used. The pump was electrically driven, and the speed could be controlled by hand. By this means an operator could keep the pressure constant to $\pm\frac{1}{2}$ per cent. while the tests were carried out.

The temperature was measured at the outlet, and for some of the tests the water was heated to 80° C. to reduce the viscosity and so obtained the highest value of $\frac{vD\rho}{\eta}$. It was found that in these high-temperature experiments the temperature variation during an experiment was less than $\pm\frac{1}{2}$° C.

In order to overcome the difficulty experienced from air coming out of solution in the pipes, freshly distilled water was used in the experiments.

In passing from one type of apparatus to the other, and when changing from one manometer to the other and from cold to hot water, overlapping experiments were carried out, so that a satisfactory cross-checking of the apparatus was obtained.

It should be noted that the only experiments not carried out at room temperature were those in which values of $\frac{vD\rho}{\eta}$ of 30,000 or over were obtained.

Pipes Tested.

There follows a description of the pipes and fittings which have been tested. In all cases the results for a pipe have been shown graphically in the form of a Stanton curve, the number of the

graph being given for each pipe. As will have been realised from the description of the apparatus, no calming section was employed, the experiments being designed to copy practical conditions. The diameters given are "effective" diameters, but this point is discussed later.

In the cases of the short pipes, the procedure was as follows: The plain pipe was first tested, and then cut up and jointed as desired and tested again. These joints were then replaced with fittings and the experiments repeated. In the following list each modification is treated as a separate pipe, but it should be realised that, in making up the pipe with elbows, etc., the original pipe was used and not a new length of similar pipe. The steel pipe was screwed with $\frac{1}{8}$-inch gas thread and the galvanised pipe with $\frac{1}{4}$-inch gas thread.

Long Galvanised Pipe.

(1) Galvanised iron. D=0·82 cm. L=1245 cm. Three lengths very smoothly jointed. See Fig. 1.

Long Steel Pipe.

(2) Drawn steel. D=0·77 cm. L=1246·3 cm. Three lengths very smoothly jointed. See Fig. 1.

Short Galvanised Pipe.

(3) Galvanised iron. D=0·80 cm. L=403 cm. Single length. See Fig. 2.

Short Steel Pipe.

(4) Drawn steel. D=0·76 cm. L=403 cm. Single length. See Fig. 2.

Short Galvanised Pipe with Joints.

(5) Pipe (3) jointed. D=0·80 cm. L=407·3 cm. There were six joints, with 61 cm. (=76·5 diameters) of pipe between joints. The joints were of screwed and socket type, assembled as is normal in practice, that is, with about 0·5 cm. of pipe screwed into the socket at each end. Sockets 2·5 cm. long. The spacing of joints was designed to imitate that occurring on larger diameter pipes (*e.g.*, in pipes 2-inch diameter, 12-feet lengths, the joints will be 72 diams. apart). See Fig. 2.

Short Steel Pipe with Joints.

(6) Pipe (4) jointed. D=0·76 cm. L=407·3 cm. Six joints, with 61 cm. of pipe (=80 diams.) between joints. For type of joints see (5). See Fig. 2.

Short Galvanised Pipe with Six Elbows Spaced.

(7) Pipe (3) with elbows. D=0·80 cm. L=403 cm. (Note, the length L does not include the length of the elbows.) Six elbows spaced, with 61 cm. of pipe (=76 diams.) between each. See Fig. 3.

Short Steel Pipe with Six Elbows Spaced.

(8) Pipe (4) with elbows. D=0·76 cm. L=403 cm. Six elbows with 80 diameters of pipe between each. See Fig. 4.

Short Steel Pipe with Six Elbows Close.

(9) Pipe (4) with elbows. D=0·76 cm. L=403 cm. Six elbows with 5 diams. of pipe between each. See Fig. 4.

Short Steel Pipe with Six Enlargements Spaced.

(10) Pipe (4) with enlargements. The sections of pipe were inserted into six tubes 3·1 cm. diam., 20 cm. long.

This gives the effect of six additional entrance and exit losses, the pressure drop down the large diameter pipe being negligible. The expansions were spaced with 80 diams. of pipe between each. See Fig. 5.

Short Steel Pipe with Six Enlargements Close.

(11) Pipe (4) with six enlargements. The enlargements were as in (9), but with 5 diams. of pipe between each. See Fig. 5.

Calculation of Results.

(1) *Method of Presentation.*—The experimental figures have been used to calculate the friction factor $R/\rho v^2$ and Reynolds' number $\frac{vD\rho}{\eta}$ which are plotted on Figs. 1–5. The great usefulness of this method of plotting has now been well established, and it allows results obtained under restricted conditions, as, for instance, in these experiments to be directly applied for other pipe sizes and fluids of other viscosities.

The equation used in interpreting the results was :—

$$P = 8(R/\rho v^2)\frac{L}{D}\frac{\rho v^2}{2g} + C\frac{\rho v^2}{2g}$$

P=pressure drop (in gravitational units).
$R/\rho v^2$=friction factor.
L=length.
D=diameter of pipe.
ρ=density of fluid.
η=absolute viscosity of fluid.
v=mean velocity.
C=number of velocity heads for entrance and exit.
g=acceleration due to gravity.

The equation as given holds for self-consistant units.

In calculating the results the values for viscosity and density of water given by the International Critical Tables were used.

In all some 200 observations were made, and space precludes the reproduction of the figures.

(2) *Diameter.*—The use of the correct diameter is a matter of the greatest importance. As can be readily seen from a re-arrangement of the above equation,[3] if the value taken for the diameter is increased by 1 per cent. the values of $R/\rho v^2$ obtained by calculation will be increased to $(1{\cdot}01)^5$ or by 5 per cent., while the value of $\frac{vD\rho}{\eta}$ will be decreased by 1 per cent.

There are two ways of obtaining the diameter of a pipe: (*a*) From the mean cross-sectional area by measuring the volume, *e.g.*, filling the dry tube with water and weighing; (*b*) by assuming Poiseuille's equation[4] to hold, and working out the diameter from experiments in the stream-line region.

It was found that by assuming suitable diameters for the four pipes the results of experiments could be made to be consistently on the theoretical line for stream-line flow so that the diameters as obtained by method (*b*) could be regarded with some confidence. Below is a table comparing the diameters obtained by the two methods.

Pipe.	D. by volume measurement. cm.	D. from Poiseuille's equation. cm.	% diff.
Drawn steel, 3 sections	0·77	0·77	0
Drawn steel, 1 section	0·77	0·76	1·3
Galvanised iron, 3 sections	0·863	0·82	5·0
Galvanised iron, 1 section	0·82	0·80	2·5

The three sections of the galvanised pipe were selected at random from the stock of ordinary commercial pipe, of equal length, and had diameters 0·82, 0·817 and 0·950 cm. For a tube of varying cross-section the mean diameter as obtained by method (*a*) is not the correct one to use, since the pressure drop varies as $\left(\frac{1}{D}\right)^4$ and the value for D required is the one which will make $\Sigma\left(\frac{1}{D}\right)^4$ correct. This can be obtained by calculation if sufficient is known about the variation of the diameter of the pipe. Assuming

[3] $Q = \frac{\pi\sqrt{g}}{8}\sqrt{\frac{D^4P}{(R/\rho v^2)\rho L}}$

[4] $Q = \frac{\pi D^4 g P}{128\eta^2 L}$

the three sections to be uniform in themselves, this calculation was made for the long galvanised pipe, and gave a value for the diameter 1·5 per cent. less than that given by method (*a*). Deducting this from the percentage difference for the 3-section pipe leaves a difference 3·5 per cent. Thus for the two galvanised pipes we may say that the discrepancy between the two diameters is approximately 3 per cent. In the case of the drawn steel pipe the diameters agree very much better, but there is a discrepancy between the differences in the two cases for which we have been unable to find a reason.

There are various possible reasons for this disagreement in the diameters of the rough pipe. If the diameter as measured by volume is used to calculate the value of $R/\rho v^2$, it will have a higher value than the theoretical in the stream line region. Whatever effect is causing the added resistance it does not appear to be any form of turbulence in the pipe, since the experiments show that the pressure drop is strictly proportional to the velocity, which is characteristic of stream-line flow. One possible explanation is that with repeated enlargements and contractions, such as occur in an extremely rough pipe, the flow while remaining eddy-free will be such that the streamlines will not be parallel to the axis of the tube, and an increased pressure drop would result from this, owing to the velocity distribution in the cross-section departing from the parabolic form demanded by Poiseuille's equation.

A second possible cause is that the mean diameter as obtained in experiment (*a*) should not be used, but a diameter making $\Sigma\left(\frac{1}{D}\right)^4$ correct, as in the case of the 3-section pipe above. Making reasonable assumptions as to the variation in diameter due to the roughness, the effect due to this was calculated, but, as would be suspected, it was found to be very small.

Thirdly, the increase in surface may have some effect, but it is difficult to see how this can be so, unless there is slip at the walls, which is highly improbable.

The first suggestion appears to be the most probable. In the state of uncertainty in which the question remains the authors have used the "effective" diameter as obtained by method (*b*) in calculating the results. This has the merit of bringing the results for the plain pipe on to the theoretical line for stream-line flow, with increased facility in calculating the results for the effect of fittings in this region.

If, however, it is desired to transfer the results for the rough pipes to the diameter as obtained by volume measurement, corrected, in the case of the long pipe, for variation in the diameter

of the three sections, the values of $R/\rho v^2$ should be increased by 16 per cent. [$= [(1{\cdot}03)^5 - 1] \times 100$], and that of $\frac{vD\rho}{\eta}$ decreased by 3 per cent. throughout the whole range. This is a simple operation on the logarithmic scale used, and will result in a line of the same shape parallel to and above that in the figure.

(3) *Entrance and Exit Loss.*—In the case of pipes with fittings, the first fitting was placed at 61 cm. from the pipe entrance. Sufficient distance was provided in this way for the initial disturbance due to entrance to die out. Thus the entrance and exit will have the full effect in all cases, and in a preliminary calculation of the results 1·5 velocity heads were subtracted from the pressure drop for each pipe. This is 0·5 velocity head for entrance and 1·0 velocity head for exit for the turbulent region.[5] The value 2 velocity heads was used for the stream line region, the value to be used in the critical region was not known, and it was assumed

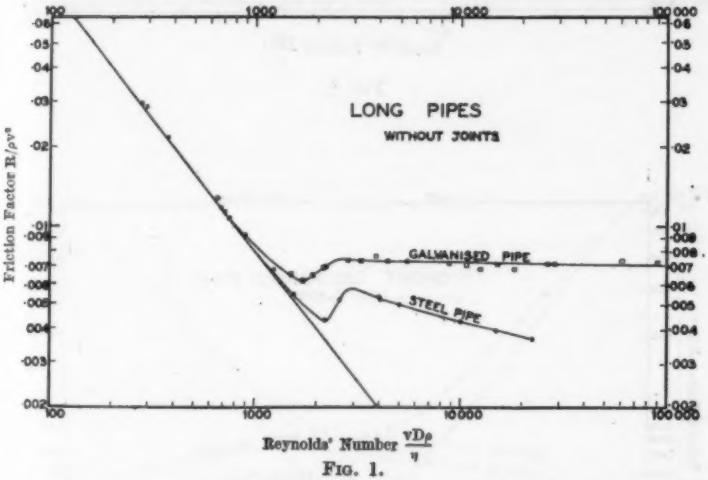


FIG. 1.

that 1·5 was correct. From the preliminary results of experiments (4) and (10) it was possible to make an accurate estimate of the entrance and exit loss over the whole range, which is shown in Fig. 7. The values so obtained were used in calculating all the results.

CONSIDERATION OF RESULTS.

Degree of Roughness.—It will be noticed that the values of $R/\rho v^2$ are highest for the long galvanised iron pipe, which is definitely

[5] "Technical Data on Fuel," 2nd ed., p. 50.

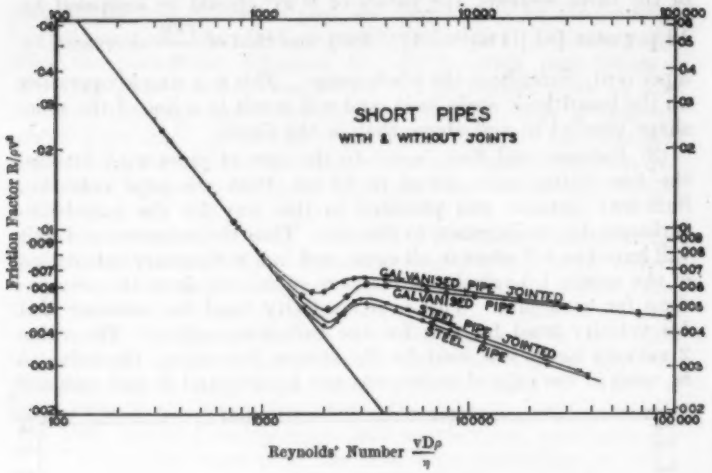

SHORT PIPES
WITH & WITHOUT JOINTS
GALVANISED PIPE JOINTED
GALVANISED PIPE
STEEL PIPE JOINTED
STEEL PIPE
Friction Factor R/ρv²
Reynolds' Number vDρ/η

FIG. 2.

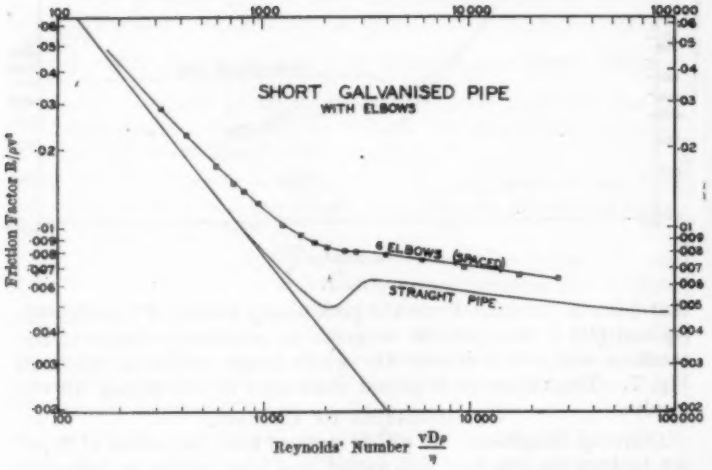

SHORT GALVANISED PIPE
WITH ELBOWS
6 ELBOWS (BRACED)
STRAIGHT PIPE.
Friction Factor R/ρv²
Reynolds' Number vDρ/η

FIG. 3.

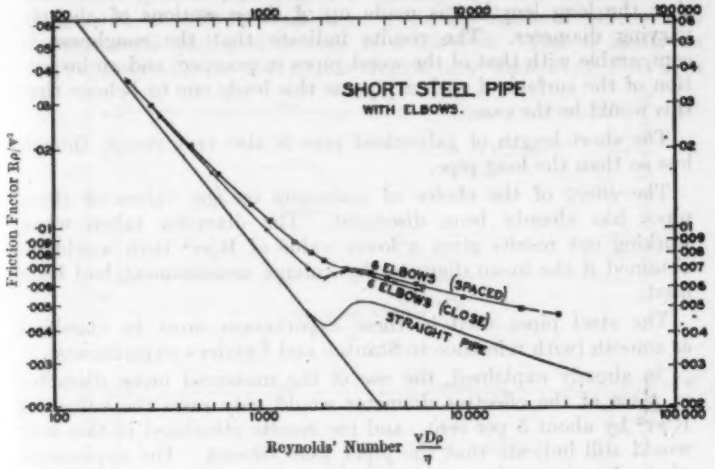

SHORT STEEL PIPE
WITH ELBOWS.
Friction Factor Rρ/v²
6 ELBOWS (SPACED)
6 ELBOWS (CLOSE)
STRAIGHT PIPE
Reynolds' Number vDρ/η

FIG. 4.

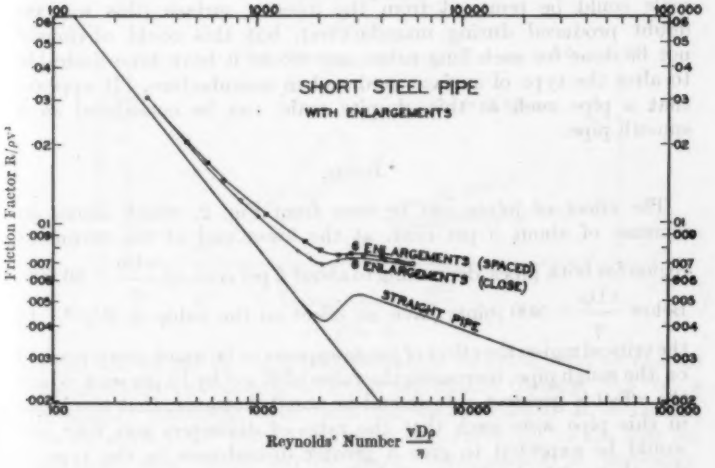

SHORT STEEL PIPE
WITH ENLARGEMENTS
Friction Factor R/ρv²
6 ENLARGEMENTS (SPACED)
6 ENLARGEMENTS (CLOSE)
STRAIGHT PIPE
Reynolds' Number vDρ/η

FIG. 5.

rougher than the short length of the same pipe, the reason being that the long length was made up of three sections of slightly varying diameter. The results indicate that the roughness is comparable with that of the worst pipes in practice, and an inspection of the surface of such a pipe as this leads one to believe that this would be the case.

The short length of galvanised pipe is also very rough, though less so than the long pipe.

The effect of the choice of diameters on the values of these pipes has already been discussed. The diameter taken when working out results gives a lower value of $R/\rho v^2$ than would be obtained if the mean diameter by volume measurement had been used.

The steel pipes used in these experiments must be classified as smooth (with reference to Stanton and Lander's experiments).

As already explained, the use of the measured mean diameter in place of the effective diameter would only raise the values of $R/\rho v^2$ by about 5 per cent., and the results calculated in this way would still indicate that the pipes were smooth. The appearance of the interior surface made this result rather surprising. Before use the pipes were carefully cleaned by pulling through a stiff wire scraper several times, and then a dry cloth, but even after this treatment the surface still appeared to be far from perfectly smooth. It was also found that a considerable quantity of hard scale could be removed from the interior surface (this was no doubt produced during manufacture), but this could obviously not be done for such long tubes, nor would it have been desirable to alter the type of surface produced in manufacture. It appears that a pipe such as this, despite scale, can be considered as a smooth pipe.

Joints.

The effect of joints can be seen from Fig. 2, which shows an increase of about 5 per cent. at the lower end of the turbulent region for both pipes, decreasing to about 2 per cent. at $\frac{vD\rho}{\eta} = 30{,}000$. Below $\frac{vD\rho}{\eta} = 800$ joints have no effect on the value of $R/\rho v^2$. In the critical region the effect of joints appears to be much more marked on the rough pipe, increasing the value of $R/\rho v^2$ by 12 per cent. where the effect is greatest. It should be noted, however, that the joints in this pipe were such that the ratio of diameters was 0·68 and would be expected to give a greater disturbance to the type of flow than with the drawn steel pipe, where the ratio was 0·9. The

value of $R\rho v^2$ in this region is greatly affected by disturbing influences, as will be seen later when the effect of elbows and enlargements and contractions is considered. This is really to be expected, for in the critical region any turbulence due to a

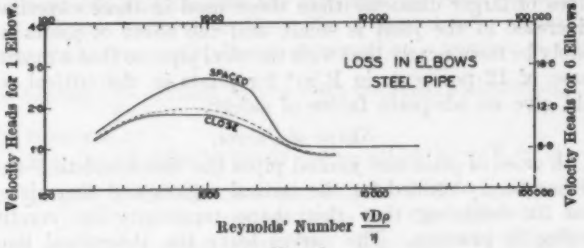


FIG. 6.

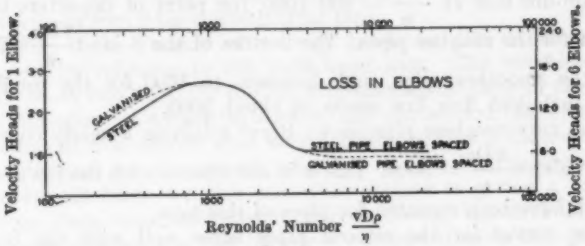


FIG. 7.

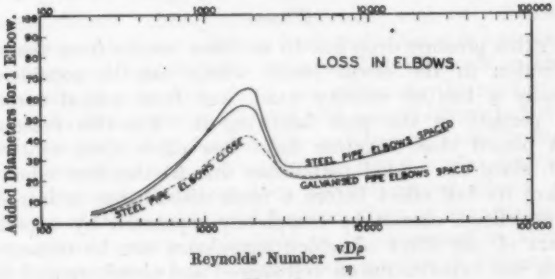


FIG. 8.

fitting will persist in the pipe following it and will tend to change the character of the flow from practically stream line to a thoroughly turbulent state, and can be considered as increasing the value of $R/\rho v^2$ from the stream-line curve up to the line for turbulent flow, both curves being extrapolated if necessary. This change in the *type* of motion due to a fitting in the critical

region has a greater effect than a corresponding increase in the turbulence if the flow is already turbulent. As already mentioned, when the cross-section of the joint shows a large increase over that of the pipe, the disturbance will be most marked. In practice, in pipes of larger diameter than those used in these experiments, the increase in the joint is small, and the effect of joints would probably be more nearly that with the steel pipe, so that a maximum increase of 12 per cent. in $R/\rho v^2$ for joints in the critical region should give an adequate factor of safety.

Shape of Curves.

In all cases of plain and jointed pipes the characteristic S-shaped bend has been obtained for the critical region, and there is every reason for believing that this shape represents the conditions occurring in practice. The curves leave the theoretical line for stream-line flow at $\frac{Dv\rho}{\eta} = 800$–$1000$, the point of departure being lower for the rougher pipes. The bottom of the S is at $\frac{vD\rho}{\eta} = 2200$. for the smoothest pipe, and decreases to 1600 for the roughest. The turbulent flow line starts at about 3000.

The very roughest pipe shows $R/\rho v^2$ attaining a nearly constant value above $\frac{vD\rho}{\eta} = 5000$. This is in accordance with the few results which have been reported for pipes of this type.

The curves for the smooth pipes agree well with the family of lines drawn from the results obtained by other workers in Fig. 11.

Elbows.

The extra pressure drop due to an elbow results from the change of direction in the elbow itself, which can be considered as essentially a loss of velocity head, and from added turbulence which persists in the pipe following it. For this reason, two elbows placed close together have less effect than two widely spaced, since the added turbulence due to the first elbow does not have its full effect before a fresh disturbance is introduced. The two effects cannot be completely separated by experiment, but part of the effect of added turbulence can be measured by carrying out experiments on well-spaced and closely spaced fittings as in pipes (8) and (9).

Assuming that there is a disturbance in the velocity distribution in the cross-section, analogous to a vena-contracta, a certain length of pipe must be allowed at the elbow for this effect to be completed.

A length of 5 diameters has been allowed in all cases for this, and although this length is short, no doubt some of the pressure

drop due to increased turbulence occurs in it. This, as far as can be seen, is unavoidable, and no satisfactory means of further separating these two effects can be suggested.

In these experiments the length of the pipe was the same as in experiment (4), and the line for this pipe has been reproduced in Fig. 4. From these three lines Fig. 6 was drawn, showing the pressure drop due to six elbows expressed as a number of velocity heads against $\frac{vD\rho}{\eta}$. These figures were obtained by inserting values in the equation :—

$$C = \text{No. of velocity heads} = 8\frac{L}{D}[(R/\rho v^2)_t - (R/\rho v^2)]$$

where D and L are diameter and length of the pipe (neglecting fittings), $(R/\rho v^2)_t$ is the friction factor for the pipe with fittings and $(R/\rho v^2)$ that for the plain pipe. The values of $(R/\rho v^2)_t$ were taken from the calculated experimental points, and $(R/\rho v^2)$ from the curve on Fig. 2 for the unjointed pipe.

In Fig. 6 the number of velocity heads for the six elbows is obtained by referring to the right-hand axis. The experimental points lie on two lines, the top one representing the drop in pressure with full effect of added turbulence, and the second one (dashed) that due to five elbows with added turbulence in 5 diameters of pipe only and one elbow with full effect of added turbulence. To make an allowance for this last elbow, which is giving a higher pressure drop than the closely spaced elbows, one-fifth of the difference between the two curves is subtracted from the dashed curve to give the lowest curve which represents the pressure drop due to six elbows "closely spaced," that is, with only 5 diameters of pipe after each elbow before a fresh disturbance is introduced.

If the top and bottom lines are used with the scale on the left-hand axis the pressure drop due to one elbow may be read.

The results of experiment (7) with well-spaced elbows in the rough pipe are shown in Fig. 3, and the number of velocity heads in Fig. 7. For comparison, the top line in Fig. 6 is also drawn in on Fig. 7. These two lines are both for well-spaced elbows, and it will be seen that the agreement between them is remarkably good.

If the pressure drop is required to be expressed as a number of added diameters, we may convert C=number of velocity heads to n=number of diameters, by the equation :—

$$n = \frac{C}{8(R/\rho v^2)}$$

where $(R/\rho v^2)$ is that for the pipe without fittings at the same value of $\frac{vD\rho}{\eta}$. By this means Fig. 8 has been obtained from Figs. 6 and 7. The middle line on Fig. 6 has not been reproduced. It will

be noticed that the agreement for the well-spaced elbows between the smooth and rough pipes is no longer good.

Therefore, the results indicate that, in making allowance for the pressure drop due to elbows, it is best to work in velocity heads, taking values from Fig. 7 and converting, if desired, to added diameters by the relation given above.

Entrance and Exit Losses.

The results for six entrances and exits in the drawn steel pipe, well spaced and closely spaced, are shown in Fig. 5.

The top and middle lines on Fig. 9 give the pressure drop in velocity heads for the six entrances and exits, and the bottom line, which gives the pressure drop for six entrances and exits closely spaced, was obtained as in the case of the elbows.

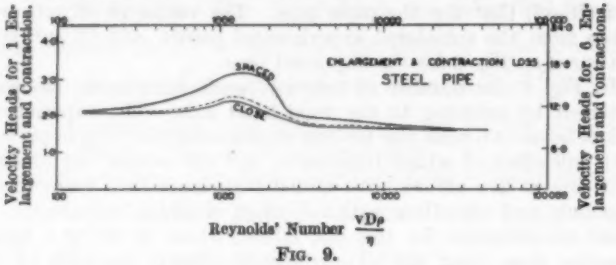


FIG. 9.

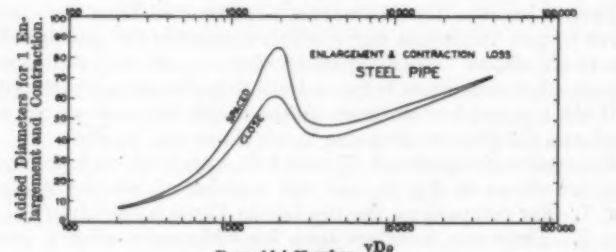


FIG. 10.

Owing to the fact that the enlargement spaces were provided by tubes of diameters about 4·0 times that of the pipe itself, the pressure drops obtained are smaller than those for entrance and exit into a large tank. It is possible to make a correction for this,[6] and for the two diameters in question it is correct to increase the experimental figures by 10 per cent. in both the stream-line and turbulent regions. For want of a better figure, this increase

[6] "Technical Data on Fuel," 2nd ed., p. 50.

has also been applied to the critical region. Using the left-hand scale in Fig. 9, the top and bottom lines give the pressure drop for entrance and exit into a large tank for the two cases where sufficient distance is given at the entrance for the added turbulence to have its full effect (top line), and where disturbance to the flow occurs 5 diameters after the entrance (bottom line). Fig. 10 shows the top and bottom lines in Fig. 9 converted to additional length.

Considering the line in Fig. 9 for the entrance and exit with full effect of added turbulence, we find that the pressure loss=2·1 velocity heads in the stream-line region, and 1·8 velocity heads at $\frac{vD\rho}{\eta} = 4000$ at the beginning of the definitely turbulent region.

The best reported value for the entrance and exit loss in the stream-line region at the values of $\frac{vD\rho}{\eta}$ covered by these experiments (*i.e.*, 200–1000) is 2·15–2·25,[7] so that the experimental agreement is good.

In the turbulent region the entrance loss, according to the best evidence available, is given by number of velocity heads = $C = 0{\cdot}5\ (1-a)$; where $a = \frac{\text{area of small section}}{\text{area of large section}}$ or for a large tank $C = 0{\cdot}5$.

The exit loss is usually taken as 1·0, but this assumes that the velocity distribution is uniform across the tube. This is not the case. The distribution has been obtained experimentally in a number of cases[8]. The loss in kinetic energy at the exit was calculated for a number of typical cases of velocity distribution, and it was found possible to construct a curve showing the variation between the theoretical exit loss and $\frac{vD\rho}{\eta}$ in the turbulent region.

The value is 2·0 in the stream-line region, corresponding to a parabolic distribution of velocity. This value decreases rapidly as the flow becomes turbulent to 1·2 at $\frac{vD\rho}{\eta} = 4000$, then more gradually to 1·1 at $\frac{vD\rho}{\eta} = 9000$ and to 1·05 at $\frac{vD\rho}{\eta} = 40{,}000$. Taking the first figure, the total entrance and exit loss would be 1·7 at $\frac{vD\rho}{\eta} = 4000$, which agrees well with the figure 1·8 obtained in the present experiment.

The curve on graph 9 has been extrapolated beyond $\frac{vD\rho}{\eta} = 6000$ in accordance with this theoretical value.

[7] See "A Monograph on Viscosity," Barr, Chap. II.

[8] Stanton, Proc. Roy. Soc., A., vol. 15, p. 366; vol. 97, p. 413. Gibson, Hydraulics, pp. 214-215.

Conclusion.

From the results given above, and consideration of those quoted in the literature, we have drawn up a new set of Stanton curves for straight unjointed pipes.[8a] These are shown in Fig. 11. There is a consistent family of curves from the smoothest to the roughest pipes, with the appropriate shape in the critical region. On the curves are marked the types and sizes of pipes for which their use is recommended. Below the graph there is a monograph for evaluating the Reynolds' number.

The dotted line represents the mean of a number of determinations on new, clean steel pipes ranging from 2–12 inches in diameter carried out by the Anglo-Persian Oil Company on natural gas lines in Persia. The accuracy of experiments carried out on the large scale in the course of refining operations cannot be expected to be as good as those done in the laboratory under ideal conditions. This line differs somewhat in shape from the family, but serves to show the dependability of the pipe sizes for which the use of the various lines is recommended.

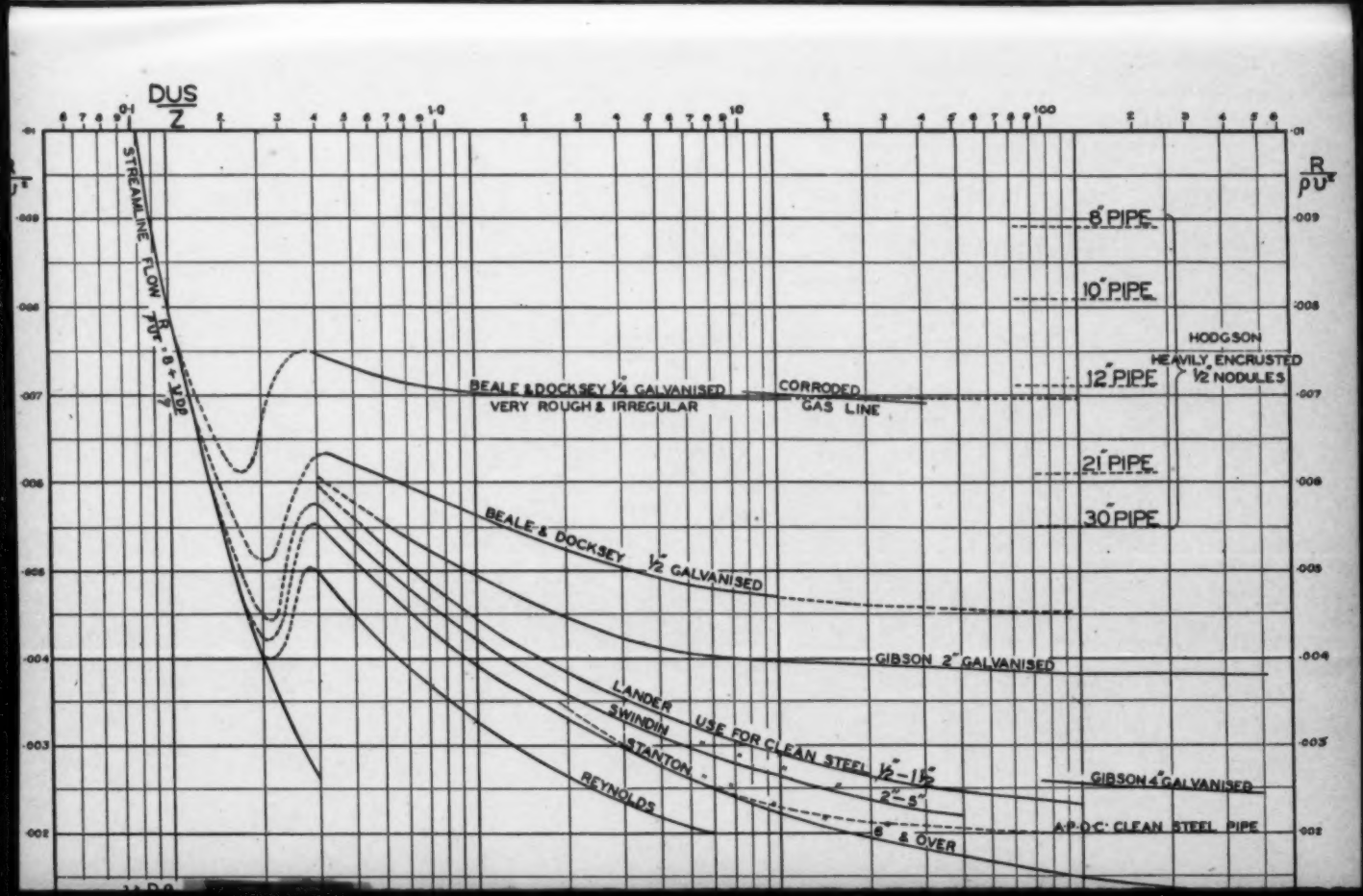
It is suggested that for jointed pipes (except for the smallest diameters) the value of $(R/\rho v^2)$ should be increased by 5 per cent. at all values of $\frac{vD\rho}{\eta}$ above 800. For small diameters the increase in $(R/\rho v^2)$ due to joints is greater in the critical region, as shown for the galvanised pipe in Fig. 2.

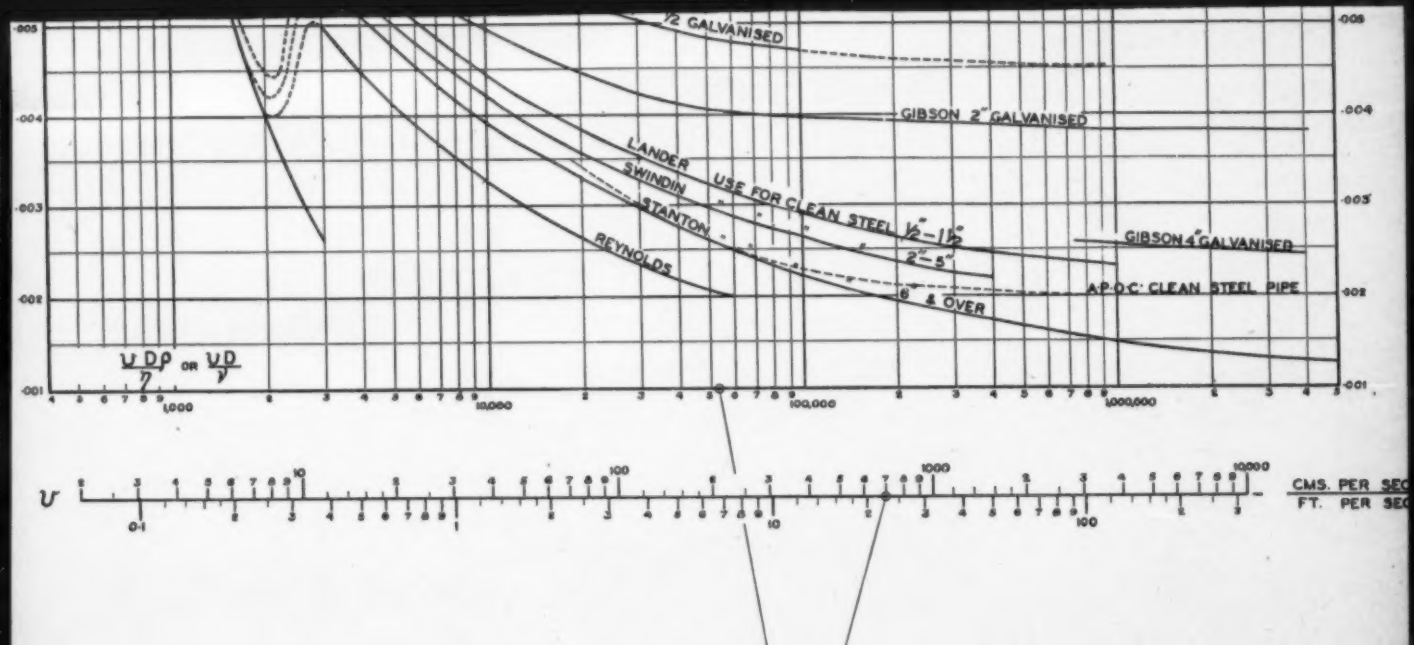
Lewis and McAdams, and Seltzer[9] have carried out a large number of experiments on elbows, and have compared their results with those of other workers. The present results are in good agreement with theirs, as can be seen by comparing Fig. 9, where the effect is represented as additional length, with the graph in their paper. In the critical region the present results are higher than theirs, and this is to be accounted for by the fact that they disregarded the S bend when calculating their results.

[8a] The following table gives the sources of the lines on Fig. 2:—

Authority.	Type of surface.	Pipe dia. in inches.	Reference.
Reynolds	Drawn lead	1/4–1/2	*Phil. Trans.*, 1883, 174.
Stanton	Drawn brass	1/7–5	*Phil. Trans.*, 1883, 214.
Swindin	Rubber hose	1	"Modern Theory and Practice of Pumping" (Swindin), p. 99.
Lander	Drawn steel	0·42	*Proc. Royal Soc. A.*, 1916, 92.
Gibson	Galvanised iron	2–4	"Hydraulics" (Gibson), p. 206.
Hodgson	Cast iron	8–30	—

[9] *J.I.E.C.*, 14, 113.


DUS/Z
R/ρU²
STREAMLINE FLOW
8" PIPE
10" PIPE
12" PIPE
21" PIPE
30" PIPE
HODGSON
HEAVILY ENCRUSTED ½ NODULES
BEALE & DOCKSEY ¼" GALVANISED VERY ROUGH & IRREGULAR
CORRODED GAS LINE
BEALE & DOCKSEY ½" GALVANISED
GIBSON 2" GALVANISED
LANDER
SWINDIN
STANTON
REYNOLDS
USE FOR CLEAN STEEL ½"-1½"
2"-5"
8" & OVER
GIBSON 4" GALVANISED
A.P.O.C. CLEAN STEEL PIPE


½ GALVANISED
GIBSON 2" GALVANISED
LANDER
SWINDIN
STANTON
REYNOLDS
USE FOR CLEAN STEEL ½"-1½"
2"-5"
6" & OVER
GIBSON 4" GALVANISED
A.P.O.C. CLEAN STEEL PIPE
.005
.004
.003
.002
.001
1,000
10,000
100,000
1,000,000
U
CMS. PER SEC
FT. PER SEC

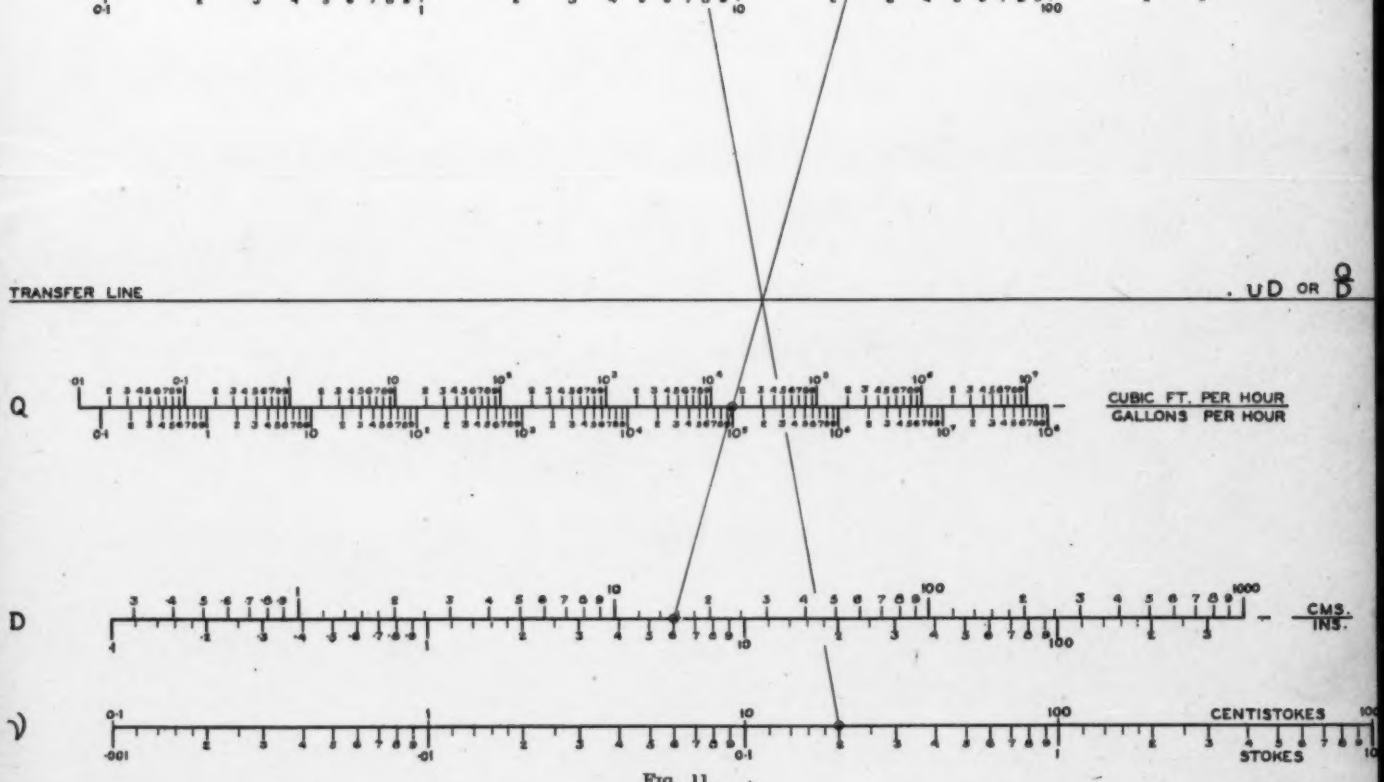

TRANSFER LINE
. UD OR $\frac{Q}{D}$
Q
CUBIC FT. PER HOUR
GALLONS PER HOUR
D
CMS.
INS.
ν
CENTISTOKES
STOKES

Fig. 11.

The velocity head method of representing the pressure drop is recommended as being more generally applicable than the additional length method, both for elbows and entrance and exit losses. The number of velocity heads for both spaced and close fittings may be obtained from Figs. 7 and 8 and converted to additional length by the following equation:—

$$n = \frac{C}{8\,(R/\rho v^2)}$$

where n = number of diameters to be added to the length, C = number of velocity heads $(R/\rho v^2)$ = friction factor used for the straight pipe.

The authors wish to thank the Directors of the Anglo-Persian Oil Company for permission to publish these results, which were obtained in their Research Laboratory at Sunbury-on-Thames.

REVIEWS

COLLOID CHEMISTRY. VOL. III. TECHNOLOGICAL APPLICATIONS. Edited by Jerome Alexander. Chemical Catalogue Co., New York, 1931. Pp. 655.

Volume I. of this monumental collation of contributions on Colloid Chemistry dealt primarily with the general theory and methods of investigation; Volume II. with the colloidics of biology and medicine; and Volumes III. and IV. complete the survey with the application of colloid methods to general chemical technology.

In the third volume is a group of eleven papers devoted to general principles, six papers concerned with mechanical or more specialised matters, and twenty-five deal with geology, mineralogy, metals, petroleum, asphalt and agriculture.

The above short summary will indicate the wealth of material brought together for the first time. There are a number of contributions of particular interest to petroleum technologists. E. F. Armstrong, writing on "Surface and Catalysis," describes the behaviour of catalysts in promoting chemical action, and develops the application of catalysts in industries that operate at high temperatures and pressures. Hugh Taylor carries the story of catalysis further and discusses the concept of active centres, lattice catalysts, the specifity of catalytic action, together with promoted and activated adsorption at reaction surfaces. E. M. James, of the Sharples Company, is concerned with the well-known super-centrifugal treatment as applied to industrial problems, in particular the dewaxing of amorphous distillates. There are three papers concerned with the application of the principles of colloid chemistry to petroleum, contributed by Jacques Morrell, Gustav Egloff and Dunstan, and a cognate article by Nellensteyn on asphalt, so that in the compass of some 40 pages a fairly comprehensive account is given of the impact of the colloidal method in the solution of many petroleum problems. In this series of papers are discussed the general colloidal nature of crude oil, of asphaltic material and of wax; the hysteresis effects shown in the viscosity relationships of residue oils, the specific adsorption of polar components on mineral gels; surface tension relationships of lubricating oils; colloidal fuels; the colloidal state of bitumen pavements, and the dispersion therein of finely divided mineral matter; the emulsification of lubricating oils and the methods of handling "cut" oils; lubricating greases, and a variety of asphaltic emulsions.

The work is extremely well produced and publishers, authors and editor are to be congratulated on a fine piece of work. A. E. DUNSTAN.

COLLOID CHEMISTRY. VOL. IV. TECHNICAL APPLICATIONS. Edited by Jerome Alexander. Chemical Catalogue Co., New York, 1932. Pp.734. $11.50.

This is the concluding volume of the series which has been issued during the past six years and the whole constitutes a piece of work of a magnitude and thoroughness which hitherto has been the peculiar characteristic of German publications. As the Editor states, although not every aspect and industry has been directly treated, so broad a field has been covered that it would be difficult to find any chemist, engineer, biologist, physician or manufacturer who could not locate much of great interest and even much of direct application to his problems.

The present volume covers a wide series of technical applications of colloids, and includes carbohydrates, plastics, sewage, photography, laundry, tanning and rubber, each section being completed by an admirably selected bibliography.

While the whole book is most readable and teems with interest, perhaps the section on carbon black has the most immediate appeal to petroleum specialists. The forty pages which constitute this chapter are contributed by Dr. Shepard of the Firestone Tyre and Rubber Company and make undoubtedly the most thorough and concise account available of the peculiar properties of the various carbon blacks and their action in creating in conjunction with rubber that wonderful colloidal solution, the motor tyre.

Methods of manufacture of channel black, acetylene black, lamp black and the other varieties of finely divided carbon are merely touched upon, for the book deals specifically with the colloid aspect of its subjects, but it is evident from the data and opinions quoted that the wearing quality of rubber containing channel black has not yet been surpassed.

It is interesting to note that no physical test has yet been devised for assessing the value of a sample of carbon black for use in tyre manufacture. Adsorption tests have hitherto entirely failed and there is still a fruitful field for research on this important problem.

This book, like the previous volumes, has been produced, both as regards paper, printing and illustrations, in a most attractive form, and the indices and bibliographies deserve the highest commendation.

F. B. THOLE.

FUEL TESTING—LABORATORY METHODS IN FUEL TECHNOLOGY. G. W. Himus. Leonard Hill, Ltd., London, 1932. Pp. 257. 15s.

Largely this book, as the Author states, is the result of experience in the application of the principles of fuel technology to large boiler plants, his notes and typed instructions used in practical teaching forming its basis. Mainly it is concerned with coal analysis, in the widest sense, and calorific value, but it is by no means confined to coal for boiler plants, for coal for

carbonisation purposes, assay for this, caking index, etc., are adequately dealt with. Whilst not confining himself to "Official" methods, those of the British Engineering Standards Association (now British Standards Institute) and of the Fuel Research Board quite properly form the backbone of the book. It is very useful to have these collected in one volume.

Petroleum fuels receive scanty treatment; probably they have not come within the Author's "experience in the application . . . to large boiler plants." In the chapter on "Oil Fuel Testing," nine pages cover the I.P.T. methods for heavy fuel oils, with, in addition, eleven lines under the determination of calorific value. Here little practical help is given, for the gist of these few lines is that "liquid fuels of high flash point may be weighed out directly into the bomb." Such matters of importance as the handling of heavy asphaltic oils or the best means of ignition are not touched on. The more volatile types of liquid fuels are dismissed in a few lines covering the use of gelatine capsules.

In the section on Gas Analysis will be found a short description of Analysis by fractional distillation at low temperatures (U.S. Bur. of Mines Tech. Paper 104, 1915), a method of considerable importance to petroleum technologists.

For those in control of coal-burning plants this book will prove of practical value, and the last chapter, "The Selection of Coal for Industrial Purposes," admirably illustrates the practical application of the various analytical and other results of the preceding chapters. J. S. S. BRAME.

ERRATA.

Page 430. Lines 22 to 24 should read: "Paraflow" is a pure hydrocarbon lubricant and is said to consist of a condensation product of fully chlorinated 125° C. m. pt. paraffin with naphthalene.

Page 432. Line 13 should read: Under comparable conditions in monel metal, propylene was found to decompose.